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See Attached N/A Supplemental Information Sheet for Additional Requirements.

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Date 3/9/88

Project No. E-25-M04 School/~~XXX~~ ME

Includes Subproject No.(s) N/A

Project Director(s) S. Dickerson GTRC/~~GIT~~

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Title Three Degree-of-Freedom Light-Weight High-Speed Robotics

Effective Completion Date: 12/27/86 (Performance) 12/27/86 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Copy of Last Invoice Serving as Final
- [ ] Release and Assignment
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DESIGN AND CONSTRUCTION OF A THREE DEGREE-OF-FREEDOM LIGHTWEIGHT PASSIVELY-DAMPED ROBOT ARM

A THESIS

Presented to

The Faculty of the Division of Graduate

Studies and Research

By

Charles Mead Tomlinson

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

Georgia Institute of Technology

March, 1987

DESIGN AND CONSTRUCTION OF A

THREE DEGREE-OF-FREEDOM LIGHTWEIGHT

PASSIVELY-DAMPED ROBOT ARM

Approved:

Dr. Stephen L. Dickerson, Chairman

Dr. Wayne J. Book

Dr. Charles Umeagukwu

Date approved by Chairman: ________

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SUMMARY

Robot manipulators are traditionally designed with structurally rigid links in order to simplify their control algorithms. A manipulator with flexible links has the advantages of higher speed and lower cost, but the structural vibrations in such a manipulator must be suitably controlled. One way of accomplishing this is to implement a control strategy which uses active control to handle low-frequency oscillations, and a passive damping mechanism to attenuate high-frequency vibrations. Such a system is well suited for inexpensive low order controllers that use relatively long computer cycle times.

This thesis presents the design of a lightweight three degree-of-freedom SCARA type robot arm that is intended to be controlled by a combination of active and passive means. The links of the arm are treated with a passive damping mechanism that uses a constrained viscoelastic layer to damp high-frequency vibrations. The arm has a total weight of 60 kg ,a rated payload of 30 kg., and a maximum reach of 68 inches. The arm design incorporates strain gauge feedback for the active control system.

The design and construction of the arm are documented, along with the electronic hardware and software necessary to move the arm. Informal tests of the arm are conducted and the results presented.

CHAPTER I

INTRODUCTION

Robot manipulators have traditionally been designed with linkages that are sufficiently stiff to be considered rigid from a control standpoint. Robots designed with lightweight, flexible links, however, have the advantages of superior speed, lower power consumption, and lower construction costs when compared to a traditional robot with the same payload rating. This project is part of an intensive research program at Georgia Institute of Technology aimed at developing design strategies for the practical application of lightweight manipulators to industry.

The manipulator described in this study was constructed to demonstrate the practical implementation of a three degree-of-freedom flexible manipulator. The design incorporates a passive damping treatment to control the high-frequency vibrations inherent in a high speed flexible arm. Other aspects of the arm design include strain gauge feedback (used to determine link deflections) and a very high payload-to-weight ratio.

The arm is a modified SCARA type, with a maximum reach of about six feet. The maximum design payload is 30 kg, which the arm can accelerate at up to 1.0 g. The total arm weight was about 60 kg, compared to the 600 to 800 kg weight of a typical industrial robot with a comparable load rating.

The arm presented in this study will eventually be used to develop and test a refined control scheme combining passive damping, active deflection control, and feedforward of joint torques. The arm was developed in conjunction with Cybotech Corporation and may be developed further for industrial use.

CHAPTER II

DESCRIPTION OF MECHANICAL HARDWARE

The mechanical hardware used in this project can be separated into four component systems; a base drive assembly, a vertical drive assembly, an elbow joint, and two tubular links. The mechanical schematic diagram is shown in Figure 1. The arm has three degrees of freedom. The base drive assembly allows rotation about a vertical axis. The vertical drive assembly is attached to the output shaft of the base, and is connected to an elbow joint by an aluminum tube. The elbow joint permits motion over an angular range similar to that of a human left elbow. A longer aluminum tube extends from the elbow joint to a mass of up to 30 kg which serves as a payload.

Base Drive Assembly

The prime mover in the base assembly is a PMI DC electric servo motor. The motor is connected to a harmonic drive speed reducer which drives a vertical output shaft. This shaft is supported by a ball bearing which is located in a cylindrical steel housing. The mechanical layout of the base drive assembly is shown in Figure 2.

A Dynamics Research Model 152 optical encoder is coupled to the motor. This encoder produces 500 counts per

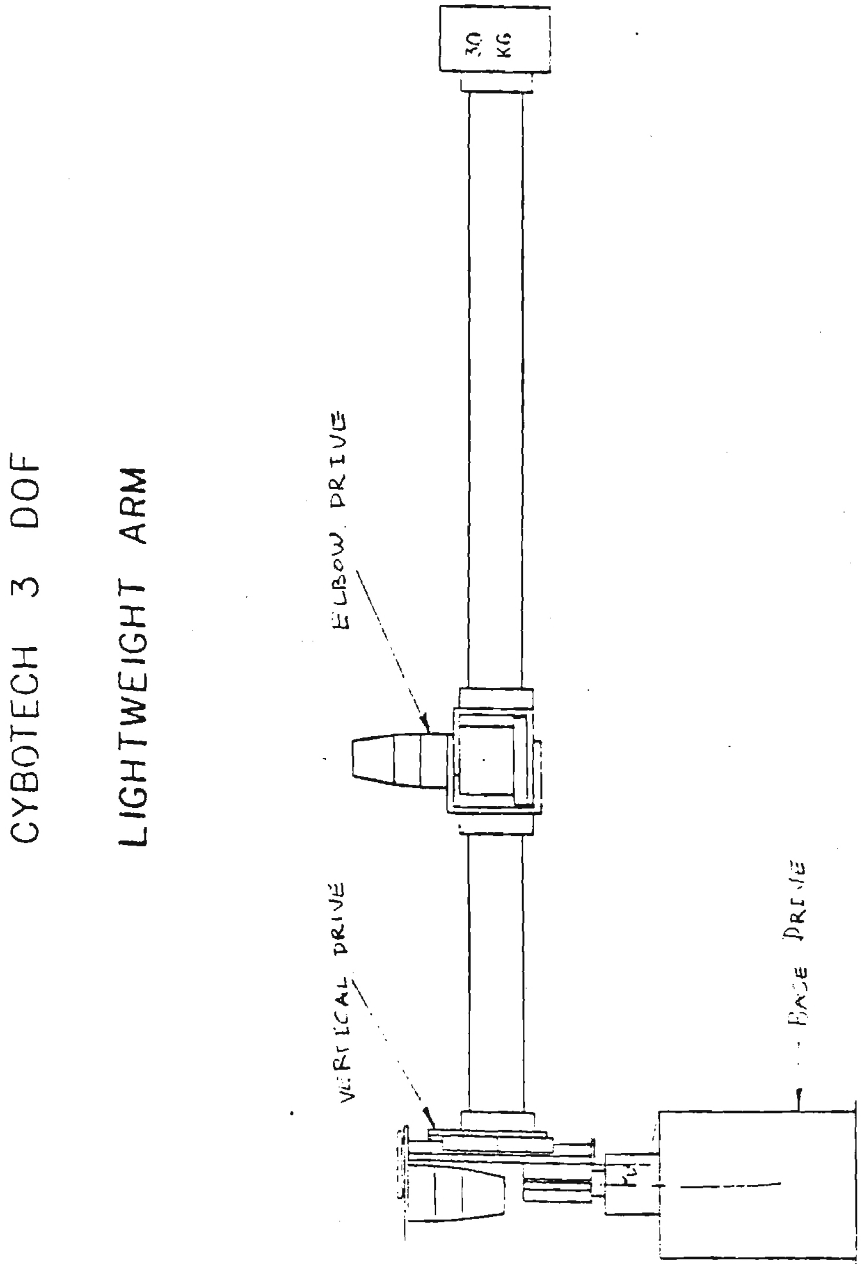


Figure 1. Mechanical Schematic of the Arm

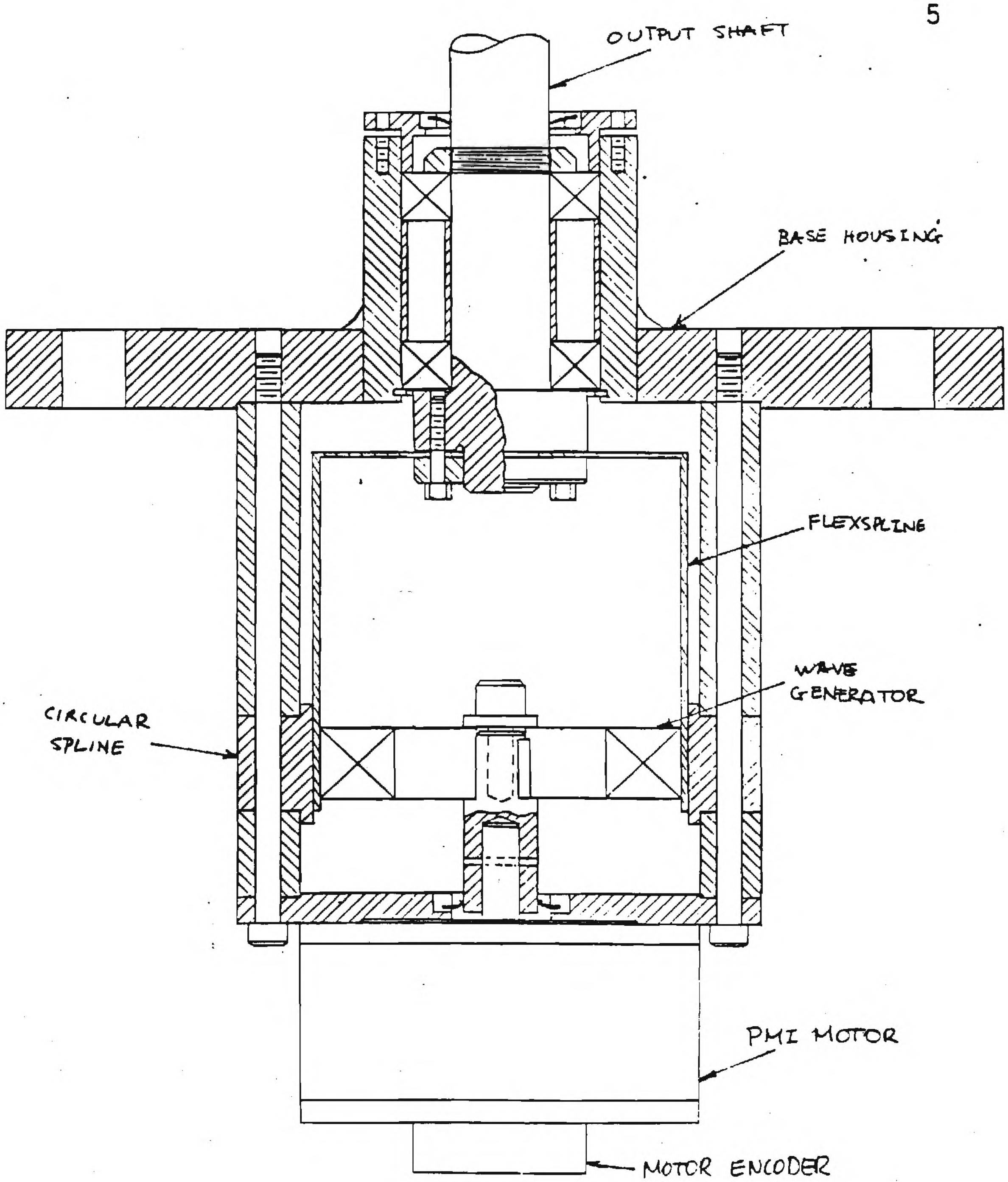


Figure 2. Layout of Base Drive Assembly

shaft revolution. These counts are output as complementary square waves and can be therefore be used to generate 2,000 counts per shaft revolution using external 4X circuitry. Further specifications for this encoder can be found in Appendix A. A tachometer was mounted outside the base housing, but was not used for this project.

The motor in the base is a PMI Model U12 M4H with a rated torque of 15.5 in-lb. at 3,000 rpm. The motor transmits power through a HDC 4M-200 Harmonic Drive unit with a speed reduction ratio of 200:1. The output torque from the harmonic drive unit is transmitted through a 1.875 inch diameter vertical shaft. A pair of clamps is attached to the vertical shaft, one of which has a flat mounting face and is used to support the vertical drive assembly. Further information on the PMI motor and mechanical drawings for the base can be found in Appendix A. Specifications for the harmonic drive unit may be found in Appendix C.

The base joint is restricted to a range of motion of about 160 degrees by means of a Micro Switch limit switch which is mounted on the output shaft of the base. The switch is activated by metal tabs mounted on the base drive housing. Activation of the limit switch causes a zero-torque command to be sent to the PMI motor controller. The range of motion of the base drive was limited to prevent disconnection of the wires that are attached to the arm. The range was set at only 160 degrees because the PMI controller sends torque (and not velocity) commands to the base motor. This fact, coupled with the fact that even 200:1 harmonic drives are easily backdriven, means that the arm requires a large angular displacement to coast to a stop from high speed.

Vertical Drive Assembly

The vertical drive assembly was mounted to the output shaft of the base. The prime mover for the vertical drive is a MAVILOR MT80 high-torque DC servo motor, with an output torque of 4.3 in-lb. at a rated speed of 1,500 rpm. The motor is equipped with a 10V/Krpm tachometer and an optical encoder that puts out 500 square wave pulses per shaft revolution. The tachometer is used only to provide feedback to the velocity-controlled motor controller that operates the vertical drive. The optical encoder output, however, is sent to the IBM-PC to be used in the computer programs that actually command the movement of the arm.

The motor drives a Saginaw ball screw through a rubber timing belt. The input and output sprockets are sized for a 2.0:1 speed reduction. The ball screw is supported at its upper end by a ball bearing which is located axially by a snap ring. The bearing is supported by a holder located above the Top Plate. Refer to Appendix B for the mechanical drawings of the various fabricated components of the vertical drive. The Top Plate is also used to mount the motor and is equipped with slots that allow the distance between the motor shaft and the ball screw to be varied to adjust the timing belt tension. The Top Plate is mounted to the top of the Main Plate, which in turn is mounted to the output shaft of the base drive. See Figure 3 for a photograph of the vertical drive assembly.

Power is transmitted by the ball screw to the ball screw nut which is located in a holder on the upper end of the Arm Mounting Plate. This plate supports the elbow joint, the two tubular links, and the payload. The Arm Mounting Plate moves vertically along a Linear Roller Way LRW 20 linear motion unit. The track rails of the LRW 20 are mounted to the Main Plate and are fixed relative to the base drive output shaft. Four slide units (two units per rail) are attached to the Arm Mounting Plate. Further specifications for the LRW 20 are contained in Appendix B.

The Main Plate is made from one inch aluminum plate stock to enhance rigidity, while the Top and Arm Mounting Plates are made from thinner aluminum plate. A quarter-inch thick aluminum Stop Plate is mounted horizontally to the lower edge of the Main Plate. This plate has a plastic foam bar on its upper surface, and is intended to provide a positive stop for the Arm Mounting Plate in the event of controller failure. A Micro Switch limit switch is mounted to the Arm Mounting Plate and is activated by tabs fixed to the Main Plate near the travel extremes of the assembly.

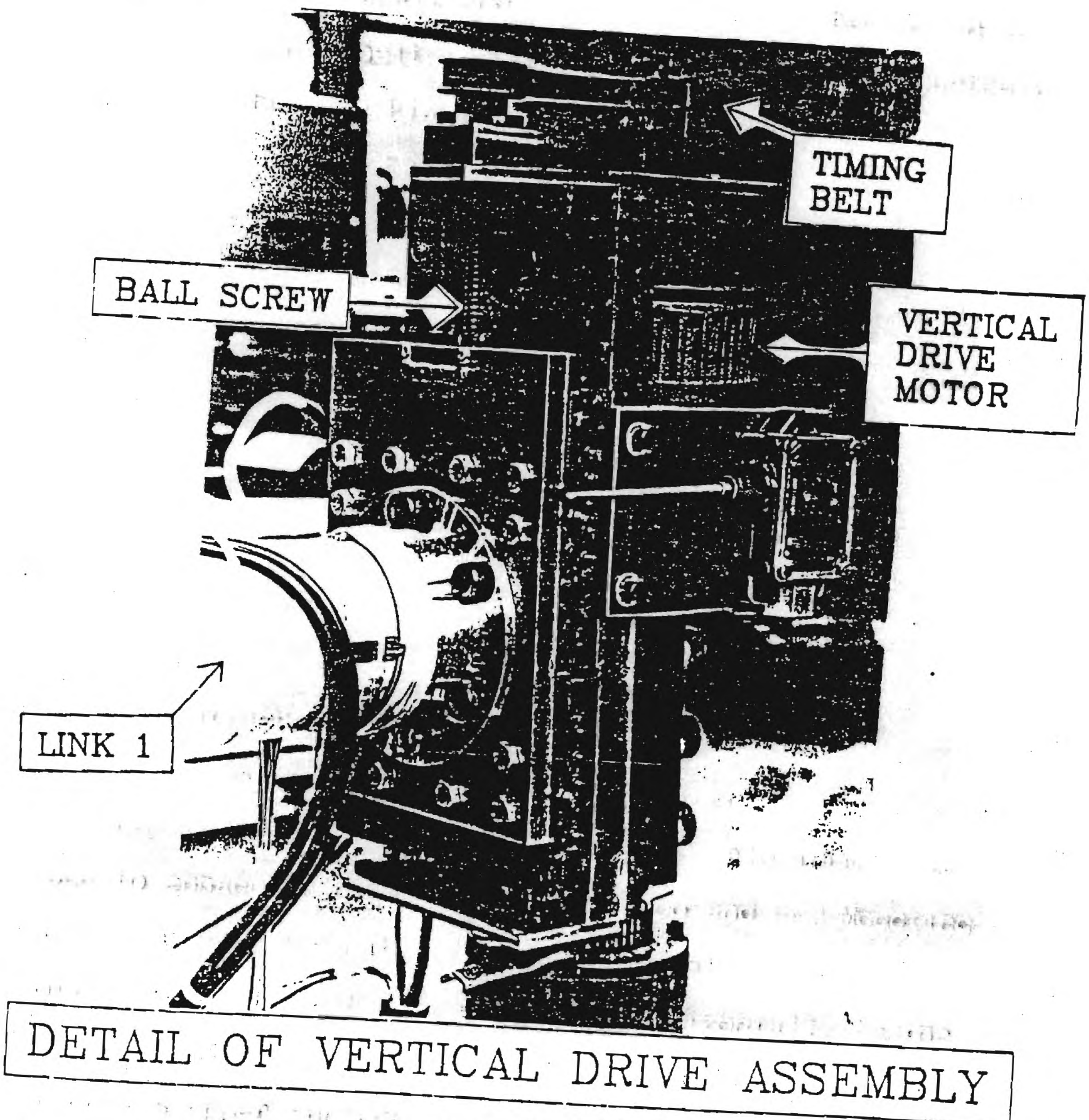


Figure 3. Photograph of Vertical Drive Assembly

Activation of the limit switch would result in a zero-velocity command being sent to the vertical drive motor controller. If the motor controller is functioning correctly, this action should result in sudden stoppage of the vertical drive. To de-activate the limit switch, the vertical drive controller must be disabled and the assembly moved manually to a position within its safe travel limits before the controller is re-activated.

Tubular Links

The shorter of the arm's two tubular aluminum links is mounted to the Arm Mounting Plate. This short link, or "upper arm" is 16 inches long between ends, and is cut from aluminum tubing with an outside diameter of 3.50 inches and a wall thickness of 0.083 inches. The link is mounted by means of aluminum flanges located at each end. Each flange has an outside diameter of 5.25 inches and has six clearance holes for 3/8 inch bolts on a 4.375 inch bolt circle. The flanges have 2.0 inch long mounting surfaces. Drawings of the flanges can be seen in Appendix D. The flanges are mounted to the ends of the tube with Scotch-Weld 2216 B/A epoxy adhesive. This adhesive has a minimum shear strength of 2,500 p.s.i. at 75 degrees Fahrenheit.

The longer of the aluminum links, the "forearm", is 44 inches long between ends, but is otherwise identical in construction to the shorter link. The forearm is mounted between the elbow joint and the payload. Both the upper arm and the forearm are treated with a passive damping mechanism, which will be discussed in the next chapter.

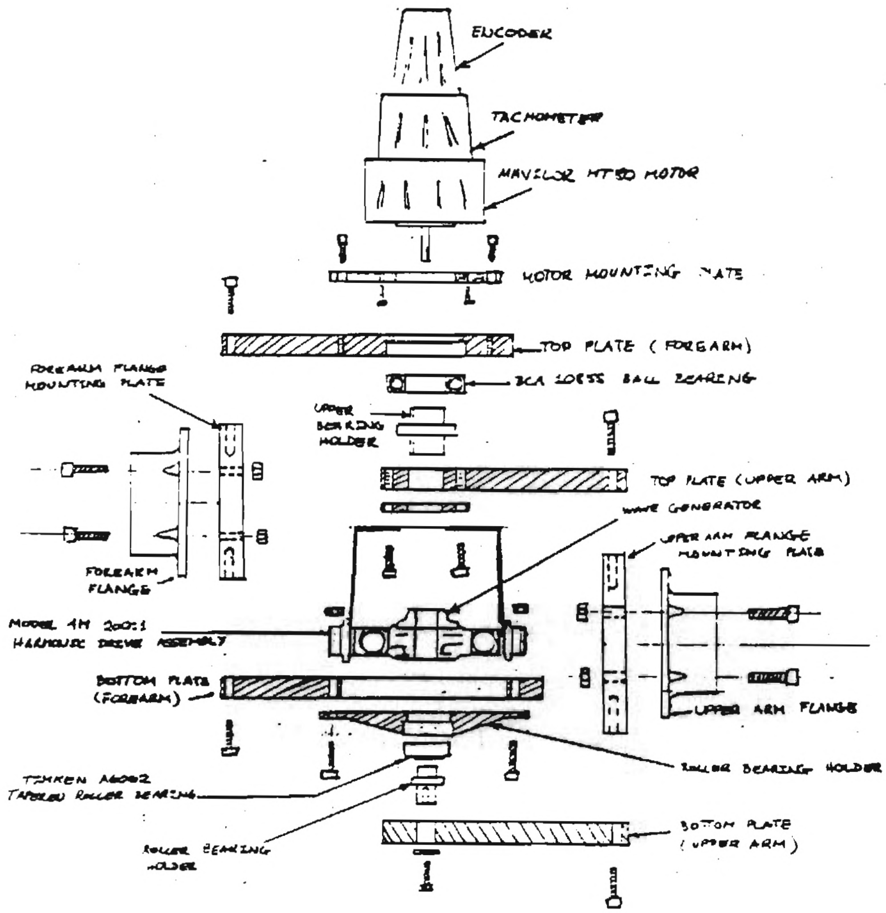
Elbow Joint Assembly

The elbow joint is located between the two tubular links. The joint is driven by a MAVILOR MT80 DC servo motor identical to the motor on the vertical drive assembly. The elbow joint motor also is equipped with the same tachometer and optical encoder as the vertical drive unit. The elbow joint tachometer output is sent to the motor controller that is responsible for the elbow drive. An exploded view of the elbow joint is shown in Figure 4.

The elbow joint was designed to be relatively compact, with an angular range of motion of at least 180 degrees. The initial design, which is the subject of this study, is comprised mainly of components that were fabricated from aluminum plate stock. This design approach was chosen in order to minimize prototype cost and construction time, and to facilitate any design changes that may have been necessary. The components were constructed from relatively thick plate stock to ensure the rigidity and reliability of the prototype joint.

The elbow joint is composed of four subsystems: a 'C'-shaped frame attached to the upper arm (considered the input link), the MT80 motor, an HDC 4M-200 Harmonic Drive

ELBOW JOINT
(EXPLODED VIEW)



NOTE: THE HARMONIC DRIVE COVER AND THE COUPLING BETWEEN THE MOTOR AND THE WAVE GENERATOR HAVE BEEN OMITTED FOR CLARITY

Figure 4. Exploded View of Elbow Joint

acting as a speed reducer, and a 'C'-shaped frame attached to the forearm (considered output). In the case of the design prototype, each 'C'-shaped frame is composed of a Top Plate, a Flange Mounting Plate, and a Bottom Plate, where the Top and Bottom Plates are bolted to the Flange Mounting Plate.

The Top Plate of the upper arm (input) contains a pressed-in steel roller bearing holder. The bearing, BCA Model 108SS, is responsible for the horizontal (radial) forces acting at the top of the elbow joint. The outer race of the bearing is press fit into the Top Plate of the output link, but the inner race is allowed a sliding fit with the bearing holder since the bearing supports very little vertical (axial) load. The entire vertical force at the elbow joint and the horizontal force at the lower end of the joint are borne by a Timken Model A6062 tapered roller bearing located between the Bottom Plates of the upper arm and the forearm. The outer race of the tapered roller bearing is press-fit into a disc-shaped bearing holder which in turn is bolted to the lower side of the forearm Bottom Plate. The inner race of the bearing is snugly fit to a steel plug that is mounted to the Bottom Plate of the upper arm.

It was assumed in this study that the tapered roller bearing would have loads acting either horizontally or vertically downwards, since the maximum design acceleration in the vertical direction was limited to 32 ft/sec2. Accelerations exceeding this value in a downward sense could conceivably occur, but are outside the design limits of the arm. However, the upward forces arising from these accelerations would probably be absorbed by the harmonic drive unit and, to a lesser extent, by the ball bearing at the top of the elbow joint.

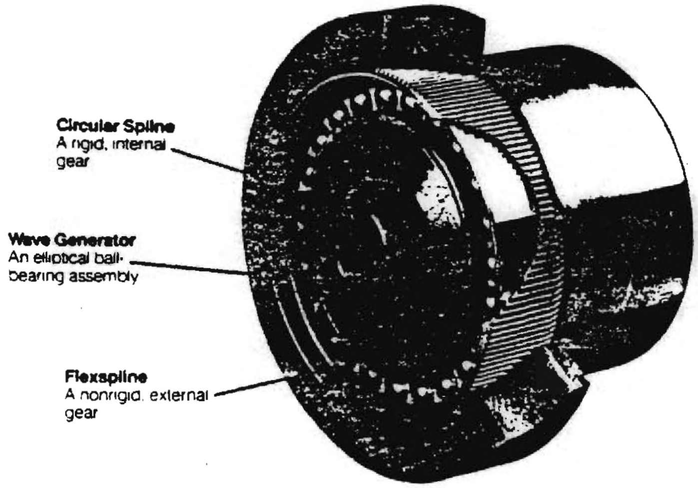
Power is transmitted from the motor to the harmonic drive speed reducer by a fabricated steel coupling. This coupling is located on the motor shaft by two set screws positioned 90 degrees apart on the upper end of the coupling. One of the set screws fits into the keyway of the motor output shaft to provide both radial and axial location of the coupling on the motor shaft. The other set screw provides additional force to secure the coupling axially. The lower end of the coupling is attached to the wave generator of the harmonic drive assembly. It is located axially by a screw and lock washer which hold the wave generator against a shoulder on the coupling. Radial location of the coupling is maintained by means of a square key fitted into keyways on the outside of the coupling and the inside of the wave generator.

The harmonic drive assembly is arranged to act as a speed reducer with a nominal numerical ratio of 200:1. Because the motor is mounted on the output side of the joint (i.e. the forearm), the effective ratio of the assembly is

201:1. The basic arrangement of the harmonic drive assembly is shown in Figure 5. In this application, the flexspline of the harmonic drive is considered fixed to the input side of the joint. The wave generator acts as the input speed member, while the circular spline is fixed to the output side of the joint. The harmonic drive mechanism is protected from dust by a 3-quart aluminum saucepan with a diameter of 8 inches. The handle was removed from the saucepan prior to installation in the joint.

The longer of the two tubular links is attached to the output side of the elbow joint. At the end of this link is a flange to which a payload can be mounted. The design payload of the Cybotech arm is 30 kg, which the arm can move in any direction at accelerations of up to 1.0 g. As mentioned previously, the arm has an angular range of motion similar to that of a human left arm. A drawing of the maximum work envelope is shown in Figure 6. The pivot axis of the elbow joint is offset from the centerline of the links by a distance of 4.0 inches. This feature allows the forearm to be rotated until it is parallel to and alongside the upper arm. The elbow design also allows about 15 degrees of "backhand" motion. In other words, the elbow can be rotated 15 degrees past the position of maximum extension. In practice, however, the range of motion of the elbow is reduced to minimize the risk of damage to the joint.

Harmonic Drive Gearing



CUP-TYPE GEARING COMPONENTS.

EQUATION #2 SPEED REDUCER

$$NC = \frac{NG}{R+1}$$

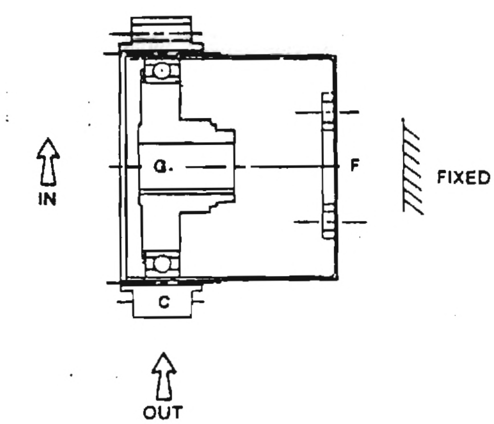


Figure 5. Harmonic Drive Speed Reducer

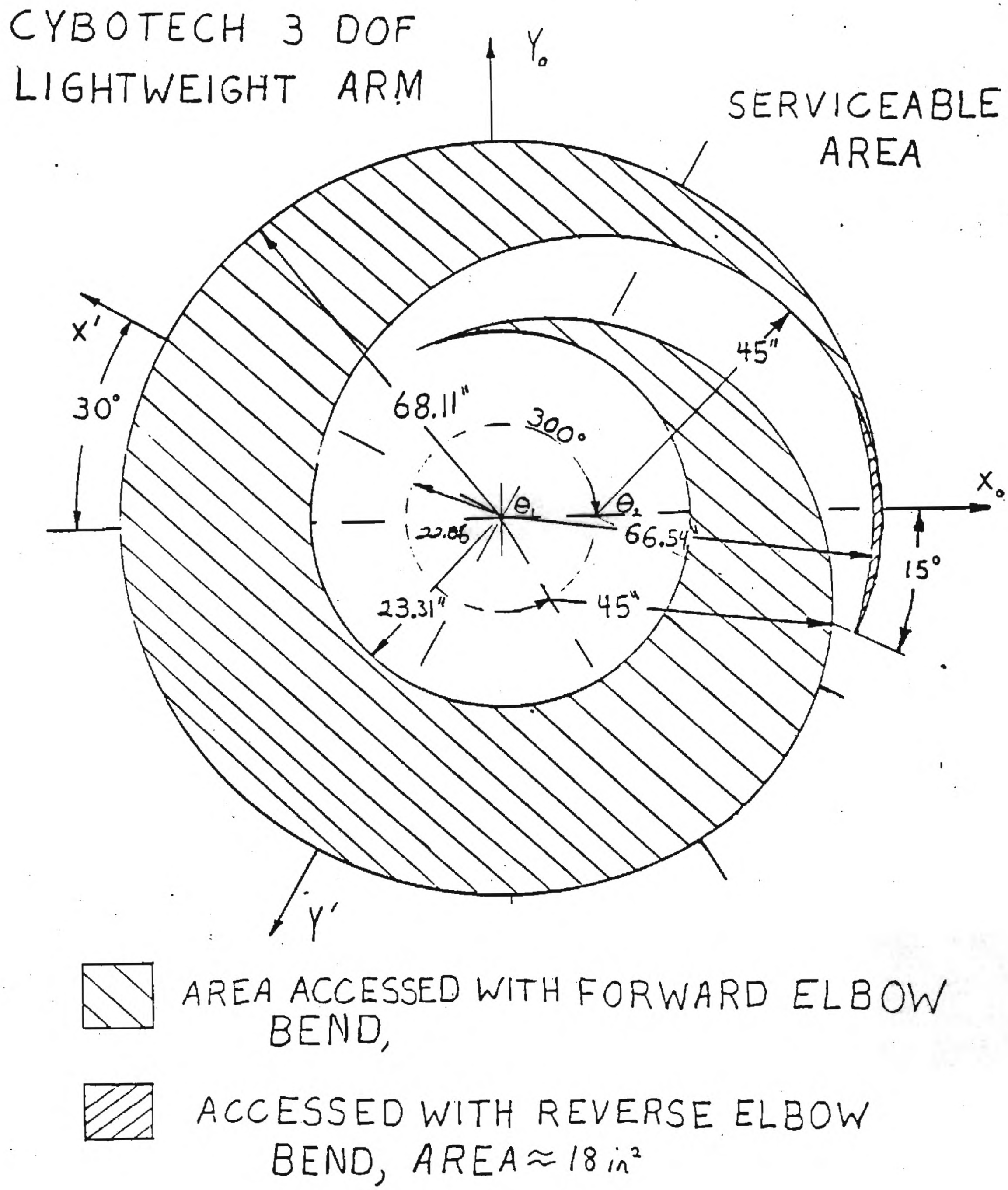


Figure 6. Service Envelope of Arm

The joint assemblies of the prototype arm were considerably oversized in terms of strength and rigidity. This design approach was chosen to ensure absolute reliability of the arm, since a mechanical failure in any of the joints could easily result in severe damage to the motors or the harmonic drive units. Furthermore, weight-saving efforts applied to the individually fabricated components of the joints would have greatly increased the machining time required for these items. Having said that, it was recognized that the joints could have been made less massive without compromising the overall integrity of the arm. For example, the actual weight of the elbow joint of the prototype arm was 35.80 lbs., including the motor and harmonic drive assembly. The target weight for the elbow had been set initially at 15.0 kg, or 33.07 lbs., so the prototype was about 8% over target weight. A weight analysis of the prototype joint is shown in Table 1.

The elbow was then examined and potential areas of weight reduction were identified. The results of this investigation are shown in Table 2. The estimated feasible weight of the joint was determined to be about 27 lbs., some 24% less than the prototype weight and about 18% under the target weight. The proposed weight reduction strategy included casting the Bottom Plates in unit with the Flange Mounting Plates. Further weight reduction could be realized by using a lighter motor assembly, since the MT80 motor

TABLE 1

ELBOW JOINT WEIGHT ANALYSIS (WEIGHTS IN POUNDS)

1.	Top Plate (Upper Arm) w/ Ball Bearing Holder	-	1.93
2.	Top Plate (Forearm) w/ Ball Bearing	-	2.55
3.	Bottom Plate (Upper Arm) w/ Roller Bearing Plug	-	2.07
4.	Bottom Plate (Forearm)	-	3.11
5.	Roller Bearing Holder w/ Roller Bearing	-	1.57
6.	Flange Mounting Plate (Upper Arm)	-	2.10
7.	Flange Mounting Plate (Forearm)	-	1.84
8.	Harmonic Drive w/ (6) 3/8" UNC Hex Nuts	-	9.04
9.	Motor-to-Wave Generator Coupling w/ Set Screws	-	0.61
10.	Motor Mounting Plate	-	0.31
11.	Motor+Tachometer+Encoder	-	8.32
12.	Nuts, Screws, Washers, and Bolts	-	1.98
13.	Harmonic Drive Dust Cover	-	0.35
	TOTAL	-	35.80
	TARGET WEIGHT	-	33.07
	PERCENT DIFFERENCE	-	+ 8.3 %

TABLE 2

ELBOW JOINT WEIGHT PROJECTION (WEIGHTS IN POUNDS)

1.	Top Plate (Upper Arm)	-	0.95
2.	Top Plate (Forearm) w/ Ball Bearing	-	1.78
3.	Bottom Plate + Flange Mounting Plate (Upper Arm)	-	2.79
4.	Bottom Plate + Flange Mounting Plate (Forearm)	-	3.94
5.	Roller Bearing Holder w/ Roller Bearing	-	1.20
6.	Harmonic Drive w/ (6) 3/8" UNC Hex Nuts	-	9.04
7.	Motor-to-Wave Generator Coupling w/ Set Screws	-	0.40
8.	Motor Mounting Plate	-	0.15
9.	Motor+Tachometer+Encoder	-	5.00
10.	Nuts, Screws, Washers, and Bolts	-	1.50
11.	Harmonic Drive Dust Cover	-	0.35
	TOTAL	-	27.1
	PROTOTYPE WEIGHT	-	35.8
	PERCENT DIFFERENCE	-	-24.3 %

package (including tachometer and encoder) is unusually heavy relative to its output. Finally, it was recognized that most of the remaining components of the joint could be made less massive with no appreciable loss in rigidity or reliability. Similar weight reduction strategies could also be applied to the base assembly and the vertical drive assembly, resulting in a total arm weight of well under 100 lbs. Even in prototype form, this arm had a weight-to-payload ratio of about 2:1, a figure far superior to that of any industrial arm. In an industrial version, some weight might be added, however, for a set of "arm pads" which would be useful for protection of the arm, nearby equipment, and plant personnel.

CHAPTER III

PASSIVE DAMPING TREATMENT AND STRAIN GAUGE PLACEMENT

One of the principal aims of this project was to demonstrate the feasibility of operating an arm which was flexible enough to exhibit large deflections with a standard payload. In order for such an arm to be operated with acceptable speed and accuracy, the deflections, including oscillations, encountered during a typical arm motion must be suitably controlled.

One method of accomplishing this is by active control. In an active control scheme, the joint positions are continuously varied in such a way as to compensate for arm deflections and move the payload along a specified path. In practice, however, the controller response time necessary to achieve an acceptably smooth path is no more than a few milliseconds. Because of practical limitations in control system sample time and prime mover response time, such fast system response is difficult and expensive to realize.

By designing a robot with a mechanism for passively damping high-frequency arm vibrations, the active control system will be responsible only for low-frequency oscillations. This allows the use of low-order controllers and relatively long computer cycle times.

Passive Damping Treatment

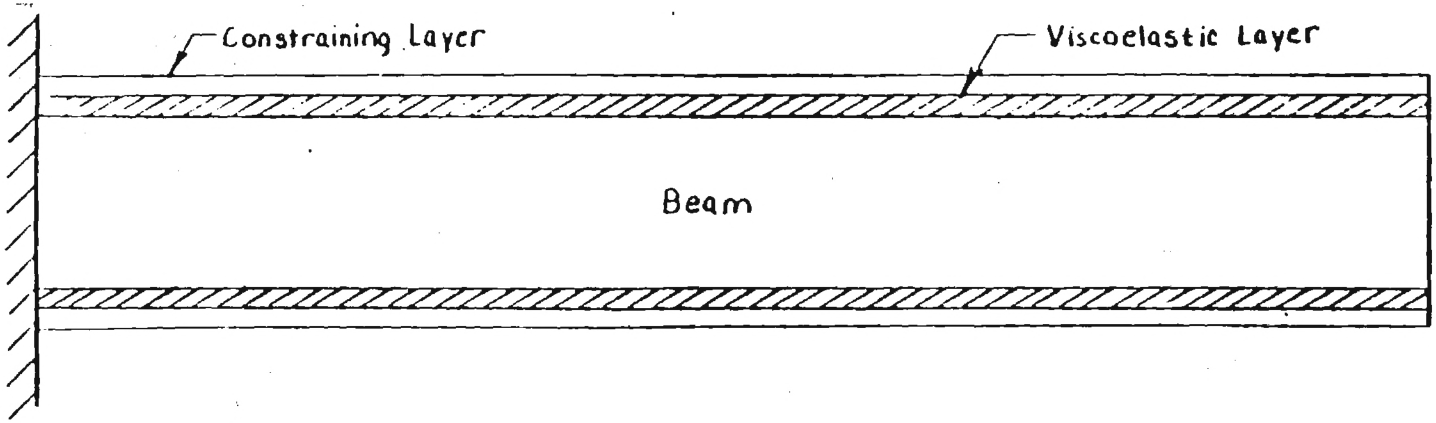
The passive damping scheme used in this project involved a layer of viscoelastic material sandwiched between the tubular link sections and an elastic constraining layer. This approach to passive damping has been studied extensively at Georgia Institute of Technology, and has been shown to be reasonably effective in the control of lightweight beams [1] especially when combined with certain active control strategies [2]. A simplified diagram of this treatment is shown in Figure 7. This arrangement causes damping through plastic shear of the damping material between the constraining layer and the beam itself. The mechanism of this plastic shear is shown in Figure 8. Studies by Plunkett and Lee [3] have shown that there is an optimum width for the constraining layer.

Lane suggested that the optimum constraining layer length for a cylindrical link is given by the following:

L = 3.28*SQRT(SQRT(1.+Ng)*T1*T2*E2/G1)*COS(TH/2.)

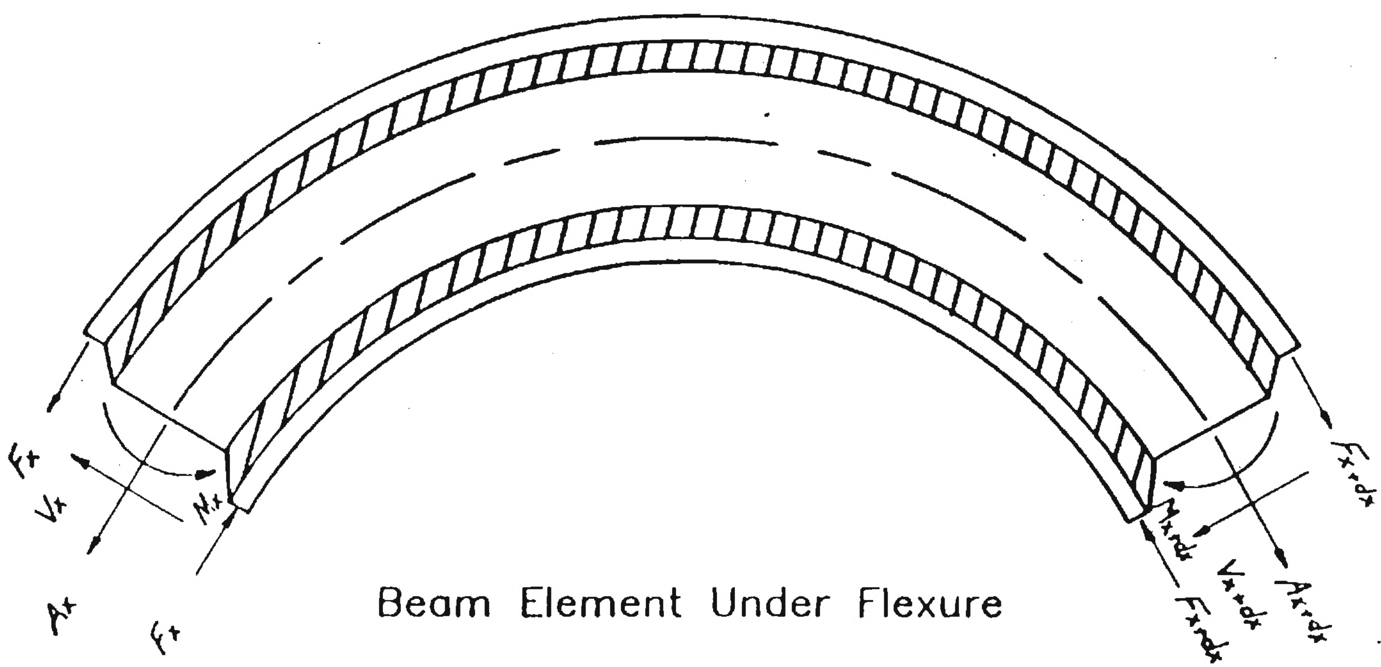
where L = optimum constraining layer length (in.),
T1 = thickness of the viscoelastic layer (in.),
T2 = thickness of the constraining layer (in.),
E2 = modulus of elasticity of the constraining layer (p.s.i.),
G1, and Ng are, respectively, the elastic shear modulus and loss factor of the viscoelastic material, which are temperature- and frequency-dependent.
TH = arctan(Ng).

Figure 7.



Viscoelastic Damping Using Continuous Constraining Layer

Figure 8.



Beam Element Under Flexure

The viscoelastic material used for this project was Scotchdamp SJ2015X Type 110, with a thickness of 0.005 inches. Further information on this material may be found in Appendix D. The constraining layer was made of steel shim stock with a thickness of 0.008 inches.

The damping was to be maximized at the second natural frequency of the arm. Using elementary beam theory for a fixed-end beam, the primary mode was found to be 4 Hz, the second at 130 Hz, with the third and fourth modes occurring at 400 and 900 Hz respectively. Using a computer program developed by S.R. Lee [4], the optimum constraining layer width was found to be 1.8 inches. The constraining layer was applied as a continuous strip, spirally wound about the link segment. This arrangement was chosen for its simplicity and to minimize the risk of separation between the constraining layer and the viscoelastic material. It is also thought to provide good torsional damping, although this has not yet been subject to analysis.

The link segments were cleaned, fine-sanded, and washed in acetone prior to application of the viscoelastic material. These steps were taken to ensure proper adhesion between the link and the damping material. After the damping material was applied to the arm, the constraining layer was spirally wound, under tension, around the link. The spiral band was applied so that the gap between adjacent strips was no more than 0.020 inch. The ends of the constraining layer were then secured to the aluminum link with Scotch-Weld 2216 B/A epoxy adhesive. During this process, the ends were heated to 200 degrees Fahrenheit with a heat gun to ensure strong bonding to the link. The entire assembly was then wrapped with duct tape as a protective measure.

Strain Gauge Placement

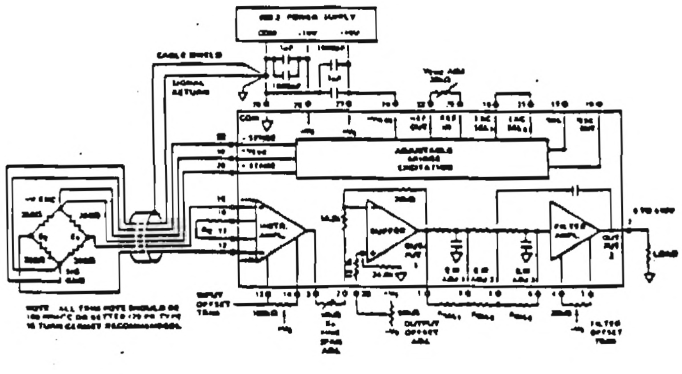
Part of the control strategy for the Cybotech lightweight arm involves the use of strain gauges to aid in estimating the position of the payload by sensing the deflection of the links. To that end, five pairs of strain gauges were mounted on the arm.

The strain gauges used in this project were made by Measurement Group, Inc. Four of the five pairs were Model EA-13-250-MQ-350 and were used to measure bending stresses. One pair of Model CEA-13-187UV-350 was used for torsion measurements [5].

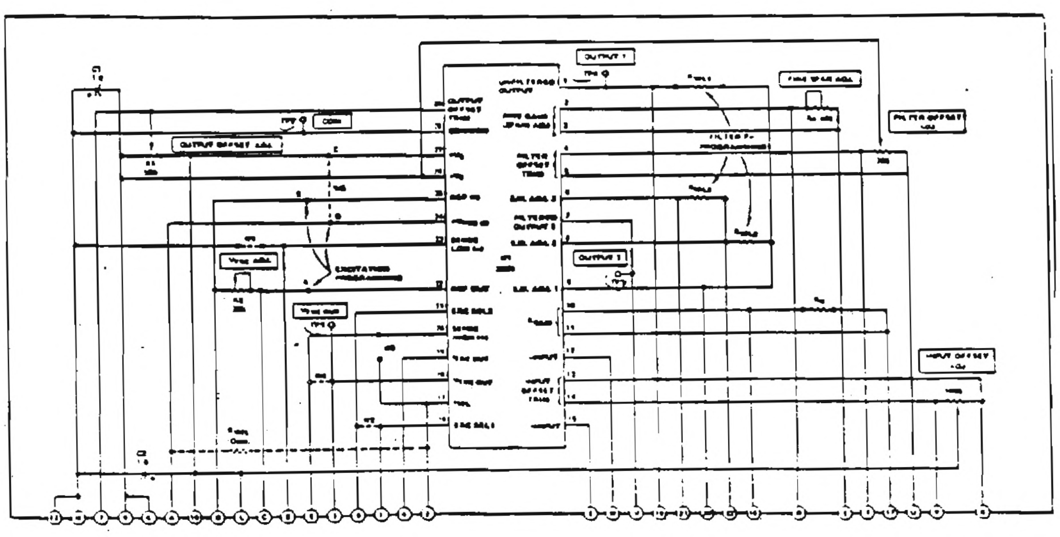
Three of the five pairs were mounted on the upper arm, approximately one inch from the flange connecting the upper arm to the vertical drive assembly. The first pair was mounted at the top and bottom of the link, and was responsible for measuring the vertical deflection of the link at that point. The second pair was mounted on the left and right sides of the link, and measured bending in a horizontal plane. The third pair was mounted at an angle of

45 degrees (between the first and second strain gauge pairs), and were responsible for torsion measurements at the root of the link.

Two more pairs of strain gauges were mounted on the forearm, about an inch from the elbow joint flange. These pairs measured vertical and horizontal bending only, since the center of mass of the fixed payload was coincident with the forearm center line, and so could not produce torsion about the forearm. The strain gauge conditioner was an Analog Device 2B31L [6]. Figure 9 shows a typical bridge transducer application using the 2B31L, and a schematic diagram of the mounting card. Specifications for the conditioner and mounting card can be found in Appendix D.



Typical Bridge Transducer Application Using 2B31L



Schematic Diagram of Mounting Card

Figure 9.

CHAPTER IV

DESCRIPTION OF ELECTRONIC HARDWARE AND SOFTWARE

When attempting to digitally control any type of system, a suitable sampling rate for the controller must be used in order to reconstruct the time response of the plant with a reasonable degree of accuracy. In the case of a flexible structure where the system to be controlled includes any of the flexible modes, the frequency of the highest mode to be controlled determines the slowest sampling rate that can be allowed.

By Shannon's principle, the sampling frequency must be at least twice the highest frequency to be controlled [7]. However, using a sampling frequency of only twice the frequency of the highest mode will generally result in poor reconstruction if the model contains any inaccuracies. For this reason, a sampling frequency of five to ten times the highest frequency to be controlled is preferred.

In the case of the Cybotech lightweight arm, the only mode to be actively controlled is the lowest mode, which has a frequency of about 4 Hertz. The higher modes of vibration are damped passively. The design sampling rate was set at 100 samples per second, imposing an upper time limit on the cycle time of the control program [8].

Much of the control program is dedicated to input and output operations. The Intel 8088 processor in the IBM-PC can handle data transfers, but while it performs the transfers, it cannot be used for computational purposes. For this reason, the IBM-PC contains an Intel 8237 Direct Memory Access (DMA) controller. The DMA controller can be instructed to perform all memory/peripheral input/output (I/O) operations so the processor will only have to handle memory/processor data transfers. Using direct memory access not only speeds up data transfer, but also releases the processor to handle other tasks.

The following is a description of the mechanics of a DMA transfer. First, a DMA transfer request (DREQ) is initiated by the peripheral device. Upon receipt of the DREQ, the DMA controller will issue a hold request (HOLD) to the processor, requesting control of the address, control, and data busses. When the processor is finished with its current I/O operation, it will issue a hold acknowledge (HOLD ACK) to the DMA controller and relinquish control of these busses to the DMA controller. The DMA controller will then acknowledge the DREQ with a DMA acknowledge (DACK) to the peripheral device. When this is done, the peripheral device sets up the data to be transferred on the data bus. Once the data transfer is complete, the DMA controller will then remove the DACK and release the HOLD, returning control of the address, control, and data busses to the processor.

During a DMA transfer, the processor can continue to perform operations as long as it does not need the control, address, or data bus. The transfers that take place under DMA control are considered 'transparent' to the processor. If the DMA controller is operating at maximum capacity, it will allow the processor to perform at least part of an instruction between DMA transfers so the controller will take about 30% of the bus bandwidth, in the worst case.

Another aspect of DMA control to be mentioned is the existence of priority levels. The DMA controller has four DMA levels, numbered from 0 to 3. Level 0 receives highest priority and is used for memory refresh. Level 1 is generally available for use with peripheral devices. Level 2 is typically used for floppy disk drive control, with level 3 typically being used for hard disk drive control. The IBM-PC used for this project was not equipped with a hard disk drive, so levels 1 and 3 were available for use.

When a DMA transfer takes place, all transfers at a numerically higher DMA level are put on hold. For instance, if a DMA transfer is in progress on level 3 and a memory refresh is required, the level 3 transfer will be suspended while a memory refresh is effected. Once the memory refresh is completed, the level 3 transfer will continue. This priority system can be changed to a rotational system, with each level 'taking turns' at operation, but a system failure could result due to excessive time between memory refreshes.

Data Acquisition Hardware

The data acquisition system for the Cybotech arm consists of a Data Translation DT 2801-A board (which contains 16 channels for analog-to-digital (A/D) conversion and 2 D/A channels), a MetraByte PDMA-16 DMA-controlled parallel port, a MetraByte DAC-02 2-channel D/A converter, and a custom fabricated 6801 microprocessor-driven quadrature board. These components are shown in Figure 10, along with the signal flow diagram.

The DT 2801-A and the PDMA-16 are capable of DMA transfers and are used on DMA levels 1 and 3 respectively. The DAC-02 is not capable of DMA transfers. The 6801 board interfaces with the PDMA-16 to transfer the decoded motor positions to the IBM-PC under DMA control. The DT 2801-A is used to perform DMA transfers of sampled analog signals, in particular the strain gauge signals originating at the joints of the arm.

The position of each motor is measured by decoding a quadrature signal obtained from the encoding circuits on each of the arm's three motors. The signal is fed into a Hewlett-Packard HCTL-2000 quadrature decoder chip on the 6801 board and is used to increment or decrement a 12-bit binary count of the position of each motor. The count is then read by the 6801 and compared with previous values to determine if either an overflow or underflow has occurred in the last time interval. If indeed an overflow or underflow

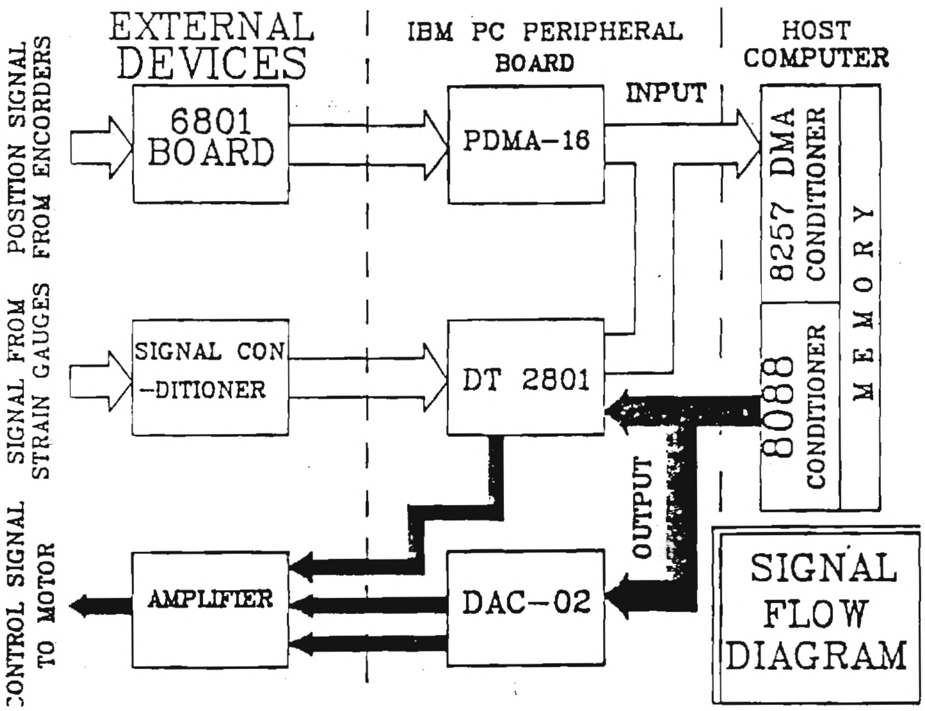


Figure 10. Electronic Hardware Signal Flow Diagram

has occurred, the high byte of the count is adjusted appropriately. The count is then fed to the IBM-PC through the PDMA-16 under DMA control and stored in specific memory locations.

The deflections of the the arm are sensed by strain gauges, whose signals are amplified and conditioned. The conditioned signals are then converted from analog to digital by the DT 2801-A. Once the conversion has been completed, these signals are also transferred to the IBM-PC under DMA control and stored in specific memory locations.

When the input operation has been completed for the cycle, the processor calculates new torques and velocities to output to the motors and does so through either the DAC-02 or the DT 2801-A without DMA. The motors in the elbow joint and vertical drive are controlled by the DAC-02 and the horizontal drive motor in the base is controlled by the DT 2801-A.

DT 2801-A Board The Data Translation 2801-A board contained in the IBM-PC contains 16 12-bit A/D channels, 2 12-bit D/A channels, and 16 digital I/O lines. The analog inputs are used to sample the strain gauges and input these voltages to the IBM-PC. The digital data, after the conversion from analog form, is put into PC memory under DMA control. The DT 2801-A is capable of doing 27,500 samples and conversions per second using DMA, so the five strain signals could be input at a maximum rate of 5,500 Hz.

Only one of the analog outputs is used on the DT 2801-A. Channel 0 is used to control the torque output of the base horizontal rotation. Use of the DT 2801-A is restricted to only one channel because of the speed limitations of the device. To effect an output from the DT 2801-A, one byte must be written to it to command a D/A transfer. The IBM-PC must then wait until the DT 2801-A is ready before it can send the first byte of the digital input. Each write operation must be followed by a waiting period to ensure that the data has been correctly received by the DT 2801-A. The digital I/O lines are accessed in the same manner as the D/A conversion lines. For this reason, a separate digital I/O parallel port was used.

<u>PDMA-16 DMA-controlled Parallel Port</u> The IBM-PC also contains a MetraByte PDMA-16 Very High Speed parallel port. This port was used in conjunction with the 6801 hardware to transfer the decoded motor positions to the IBM-PC.

The PDMA-16 was chosen because of the lengthy cycle times of the DT 2801-A. Since the PDMA-16 uses DMA, the 8088 processor is freed to perform any computations needed by the control program. Furthermore, once the PDMA-16 is programmed for I/O operations, it does need to be written to or read from again while the control program is running [9].

The PDMA-16 has a maximum data transfer rate of 350,000 bytes per second asynchronously. If the DREQ line is pulled high for each transfer, data can be sent or received faster than if the transfer were timed. The reason for this lies in the fact that the DMA controller is often able to transfer data in well under the maximum transfer time of 5 microseconds. By using the DREQ line to signal a transfer request, the DMA controller can make full use of the idle time on the busses.

The PDMA-16 can also be used as a conventional digital I/O port at any time by writing or reading the value to be transferred to or from the appropriate port on the PDMA-16.

The PDMA-16 also contains a 32-bit timer. The clock rate of the timer is 10 megahertz (MHz) and the timer is fully programmable for a frequency range of 0.002 Hz to 10.0 MHz. The timer has six output modes, with the squarewave mode being used for this application. The timer can be used to provide the IBM-PC with an interrupt but this feature was not used.

Finally, the PDMA-16 has an input line which can generate an interrupt in the IBM-PC from an external device. The interrupt can be configured by software to have any priority level from 2 through 7. This feature was not used in this project. Further information on the PDMA-16 can be found in Appendix E.

<u>DAC-02 D/A Converter</u> The MetraByte DAC-02 was chosen for this application to supplement the DT 2801-A with 2 additional analog outputs, each controlling one of the three

motors. The DAC-02 has one 8-bit register for each D/A converter [10], with the conversion occurring as soon as both the low and high bytes being sent to the appropriate register. The extremely small waiting time is one of the main advantages of the DAC-02.

<u>6801 Board Hardware</u> The 6801 board hardware schematic is shown in Figure 11. The details of the DMA handshake hardware is shown in Figure 12. This additional hardware is a result of the requirements of the DREQ signal. A detailed description of this hardware will follow the description of the 6801 board. The data sheets for the integrated circuit chips that constitute the 6801 board and the DREQ handshake can be found in Appendix E. For data sheets and references to the 6801, consult the <u>6801 Technical Reference Manual</u> [11].

The 6801 is configured for mode 2 operation. This means that the 6801 has 128 bytes of internal random access memory (RAM) located on the first page of board memory. This arrangement allows direct addressing, which is faster than extended addressing. It also has the capability to address the full 64 kilobytes (kB) of memory addresses on the 16-bit data bus. This capability allows the use of user-defined interrupt vectors, which will be discussed shortly.

The program that is executed by the 6801 is stored in a 2716 Ultraviolet Erasable Programmable Read Only Memory

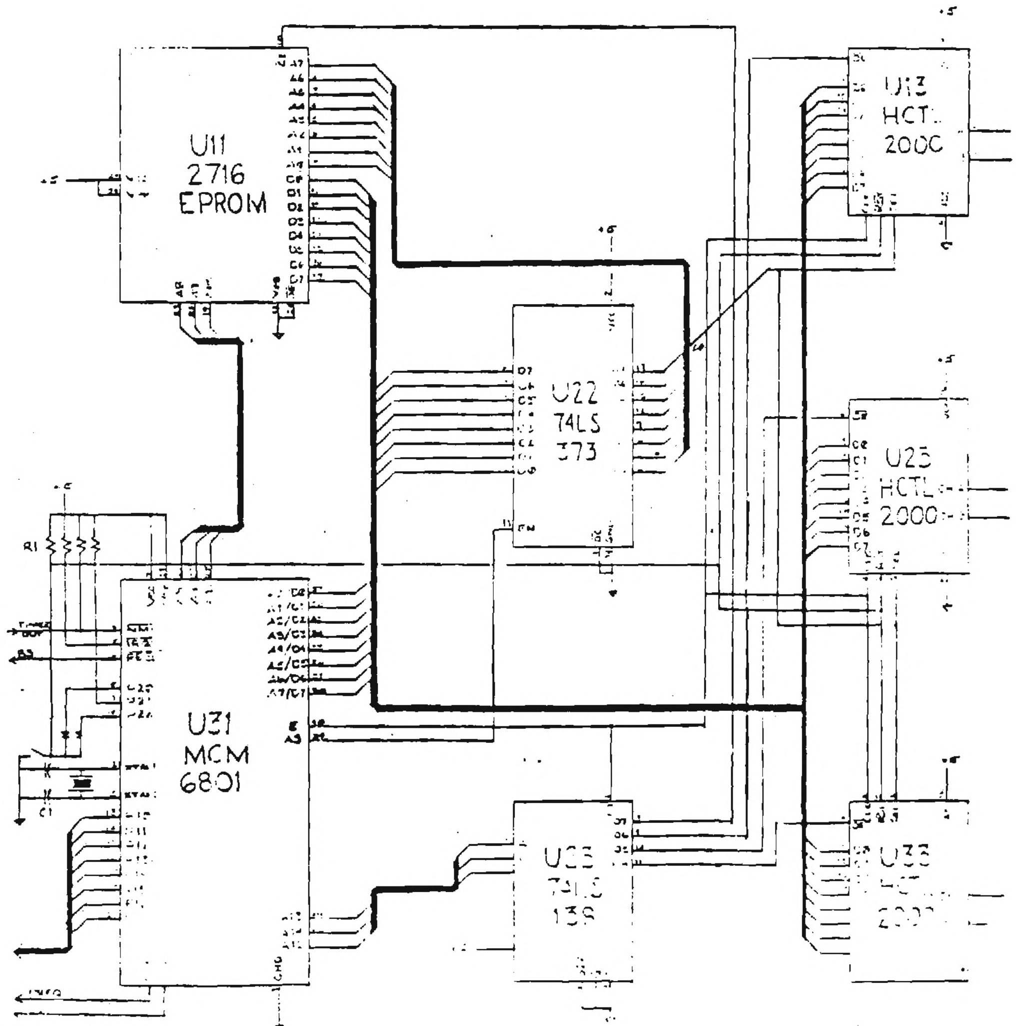


Figure 11. 6801 Board Schematic

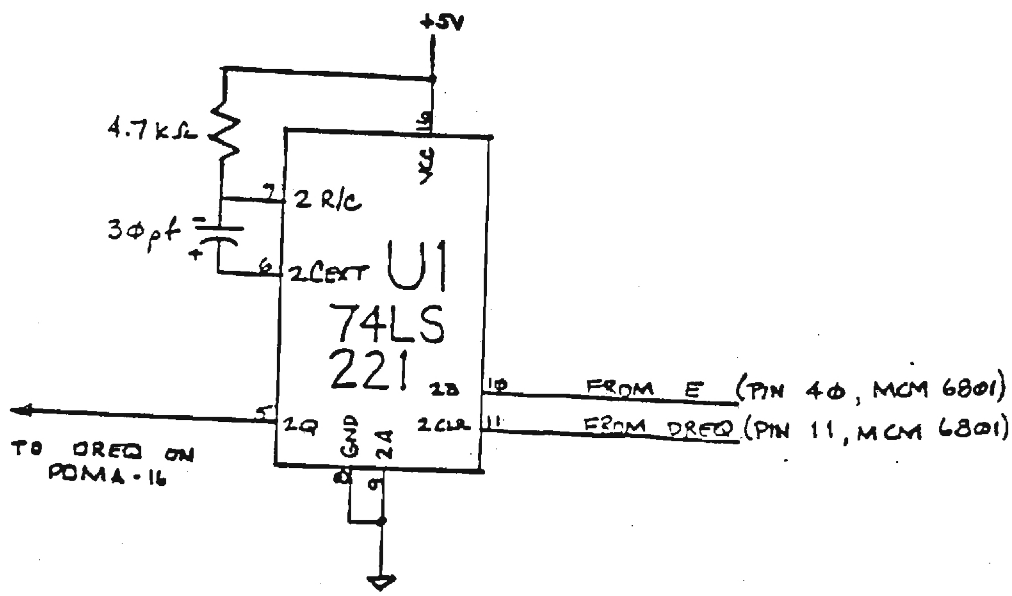


Figure 12. DREQ Handshake Hardware

(EPROM). The 2716 EPROM is set up to contain the highest 2 KB of memory in the 6801.

Due to the structure of the 6801, the data bus must be multiplexed with the lower byte of the address bus in order to access up to 64 KB of memory. In other words, the data bus sometimes serves as the lower byte of the address bus. In order to maintain a valid address for a memory read or write, a latch must be provided to hold the address while the bus receives data. The latch used in this project was the 74 LS 373. The 6801 board also contains three Hewlett-Packard HCTL-2000 quadrature decoder chips which perform the decoding of the motor positions. The output port of each HCTL-2000 is connected to the data bus and is read by a 2 byte read instruction.

In order to keep each of the devices located in the 6801 at its own unique address, a 1-of-8 selector was used. This chip was connected to the highest three bits of the address bus and selected one of the four chips that were connected to the the data bus. This allowed only one set of outputs to be enabled at any one time. The four chips connected to the data bus were the 2716 EPROM and the HCTL-2000 decoder chips.

The last chip on the 6801 board was a 74 LS 221 one-shot multivibrator. It was used to control the DREQ handshake to the IBM-PC. The minimum pulse width for reliable DREQ is 50 nanoseconds. The minimum output pulse width of the 6801 is 5 microseconds. The relatively long pulse width of the 6801 would have caused a problem if the DMA transfers were taking place in less than 5 microseconds. If that were happening, the DREQ line would still be active when each data transfer was completed. This would initiate another transfer of the same item of data, placing that byte in the next memory location in the IBM-PC. Clearly, this would result in incorrectly placed (and possibly irretrievable) data. The presence of the one-shot multivibrator ensured that the DREQ signal was long enough to activate a DMA transfer, yet brief enough to end before the DMA transfer was complete.

Data Acquisition Software

The software documented in this section handles all of the data acquisition of the Cybotech arm. The 6801 program is written in assembly language and the IBM-PC program is written in Turbo-PASCAL. Program listings may be found in Appendix F.

IBM-PC Software The DMA controller in the IBM-PC must be programmed with several pieces of information before successful data transfers could have been performed under DMA control. For example, the controller had to programmed with the page location of the data, the number of bytes to be transferred, and the location of the data's destination.

The PASCAL program DMA.PAS was used to program the DMA controller and the PDMA-16 to input the decoded motor positions. The following sequence of instructions was implemented by this program.

1) Disable the DMA level to be programmed by setting the appropriate mask register bit.
2) Set up the transfer characteristics by writing the setup to the mode register.
3) Load the address and byte count registers with appropriate data.
4) Write the page register to set the DMA active page.
5) Install any interrupt handler.
6) Set up the PDMA-16 interrupt and DMA control registers to enable interrupts and DMA (if used). Also, the DT 2801-A was set up here.
7) Reload the onboard timer (if used).
8) Enable interrupt mask register (if interrupts ae used).
9) Enable DMA mask register to activate the level that is being programmed.

The DMA mask was always enabled <u>after</u> completion of the setup, since the DMA controller would make most (or all) of the DMA transfers if it were to be activated before the PDMA-16. This would result in totally incorrect information being stored in the IBM-PC. The MetraByte PDMA-16 user manual can be consulted for a detailed description of the registers in the PDMA-16 and the DMA controller. The Data Translation user manual will provide complete information on the DT 2801-A.

The main program in the IBM-PC has an input which allows the user to easily alter the sampling rate of the controller, by using the 32-bit programmable counter in the PDMA-16. The timer is configurable for a variety of output waveforms, with a square wave output being selected for this application. The program prompts the user for the sampling frequency and sets the timer interval accordingly.

The 6801 board is driven by an edge-sensitive non-maskable interrupt called NMI. The negative edge of the square wave (i.e. the high-to-low transition) causes the 6801 to enter an interrupt service routine which contains the underflow/overflow and output routines. The highest sample rate is realized when the square wave period is exactly the same as the cycle time of the interrupt service routine. If the period of the square wave were to become smaller than this value, the 6801 stack memory would be rapidly consumed, resulting in termination of the 6801 program.

The cycle time of the 6801 routine is about 200 microseconds, but the time required for the system to respond to the output of the 6801 must be added to this value to determine the effective cycle time of the 6801 system. The time required for the calculation of the torque and velocity commands for each motor must be added to the cycle time of the 6801 board to arrive at the minimum cycle time for the entire system.

The PASCAL program JOG.PAS allows the user to set up the controllers, move each joint, disable the controllers and quit. All of these options are displayed in the main menu. Selection of these options is accomplished by keying in the first letter of the desired option.

Program JOG.PAS first commands zero voltages to each of the motor controllers to ensure that the motors remain stationary when the controllers are enabled. This step is necessary becaause the motor voltages are represented by the numbers 0 through 4095, corresponding to the voltage range -10V to +10V. Since the motor controllers would normally receive zeros upon startup, all three motors would start up at full torque, a situation which could result in damage to the arm.

The program then allows the user to move the joints by first specifying a motor speed parameter in the range 0 to 2047, then striking the appropriate keys on the PC to move any of the three motors in either direction. The program does not allow the user to move more than one motor at a time, thereby reducing the risk of inadvertently exceeding the safe range of motion of the arm. Limit switches were installed near the travel extremes of all three joints, to further protect the arm.

The program also offers disable and quit options. Both options will stop the motors and disable the controllers, with the quit option terminating program execution and returning the user to the DOS level on the IBM-PC.

6801 Board Software The 6801 board has a dedicated program in the 2716 EPROM wich will set up the 6801 to run the data acquisition program automatically upon reset. The algorithm for checking overflow and underflow is straightforward and consists of the following checks:

1) If the two most significant bits of the current reading are clear and the the two most significant bits of the previous reading were set, then an overflow occurred.
2) If the two most significant bits of the current reading are set and the two most significant bits of the previous reading were clear, then an underflow occurred.

The position encoders on the motors produce 500 complete cycles per shaft revolution. The HCTL-2000 decoder chips have internal multiply-by-four circuits which increase the count to 2,000 per shaft revolution. In the case of the elbow joint, which employs a 200:1 speed reducer, the decoders would put out about 220,000 counts during a 195 degree rotation. Since the decoders have a 12-bit capacity and so can only record 4,096 counts before overflow, they would overflow 54 times during the course of such a move. The position can be sent to the IBM-PC using a maximum of 16 bits, leaving 4 bits to keep track of decoder overflows. Since 6 bits are required to track 54 overflows, the 6801 program truncates the last two bits of the decoder outputs before sending them to the PC.

CHAPTER V

DISCUSSION OF RESULTS AND CONCLUSIONS

The lightweight three degree of freedom arm presented in this thesis was constructed and informally tested by operating the arm from an IBM-PC. The arm showed good velocity and acceleration of all three joints. During slower moves, some vibration of high frequency and very low amplitude was apparent in the forearm while the elbow joint was in operation, possibly a result of the slight velocity 'ripple' inherent in the operation of harmonic drive speed reducers. Otherwise the arm displayed smooth motion of all three joints.

The strain gauge outputs were observed to be essentially noise-free, while providing consistent and sensitive measurements of link deflections. The hardware and software responsible for motor control performed very well, although the lack of velocity feedback to the PMI base motor controller made it difficult to move the base joint at high speed without exceeding the excursion limits of the assembly and activating the limit switch.

A later version of JOG.PAS, developed by B. K. Beeson, used motor encoder feedback to the IBM-PC to enable point-to-point motion (in joint space) of the vertical and elbow joints. Position accuracy of $\pm$ 2 encoder counts was observed even during full-power moves.

The Cybotech three degree of freedom arm demonstrates the feasibility of constructing a lightweight high-performance manipulator at relatively low cost. Previous studies conducted at Georgia Institute of Technology have conclusively demonstrated the advantages of passive damping with constrained viscoelastic layers, especially when applied to flexible beams. Research is currently under way to develop practical control algorithms for lightweight robot arms with multiple degrees of freedom. The arm presented in this thesis can be used to refine such algorithms and possibly lead to the design of a system suitable for industrial applications.

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8. Beeson, Bradley K., "Data Acquisition and Control Hardware for a 3 Degree-of-Freedom Lightweight Arm," Special Project Final Report, School of Mechanical Engineering, Georgia Institute of Technology, 1986.

9. PDMA-16 Manual, Copyright Metrabyte Corporation, 1986.

10. DAC-02 Manual, Copyright Metrabyte Corporation, 1984.

11. MC6801 8-Bit Single-Chip Microcomputer Reference Manual, Second Edition, Copyright Motorola Inc., 1983.

Appendix A

BASE DRIVE ASSEMBLY

(See Fig. 2, p. 5 for partial assembly drawing)

BASE DRIVE ASSEMBLY

MOTOR:	PMI model U12 M4H, torque: 15.5 in.-lb. at 3000 rpm
ENCODER:	500 pulses per revolution (ppr)
TACH:	NOT USED
SPEED REDUCTION:	HDC 4M-200 HARMONIC DRIVE, 200 : 1 RATIO
OUTPUT MEMBER:	1 $^7/_8$ in. VERTICAL SHAFT
RANGE OF MOTION:	160° (WITH LIMIT SWITCH)

A. Characteristics for PMI U12 M4H Motor

Motor Performance: Incremental Motion Control	Symbol	Units	U12M4H
Peak Torque	TP	oz in	2109.6
Continuous Stall Torque	TS	oz in	196.9
Peak Current	IP	amps	84.5
Continuous Stall Current	IS	amps	8.13
Peak Acceleration without load	AP	krad/sec/sec	100.5
Cogging Torque	TC	oz in	0
Motor Performance: Rated			
Torque	T	oz in	185.5
Speed	N	rpm	3000.0
Power Output	P	watts	411.2
Terminal Voltage	E	volts	63.5
Current	I	amps	8.02
No Load Speed at Rated Voltage	NM	rpm	3359.4
Max Permissible Dissipation at Rated Speed	PL	watts	98.4

B. Characteristics for PMI U12 M4H Motor

Motor Constants: Intrinsic (at 25 Deg C)	Symbol	Units	U12M4H
Torque Constant	KT	oz in/amp	25.03
Back EMF Constant	KE	volts/krpm	18.50
Terminal Resistance	RT	ohms	0.750
Armature Resistance	RA	ohms	0.610
Average Friction Torque	TF	oz in	6.5
Viscous Damping Constant	KD	oz in/krpm	4.07
Moment of Inertia	JM	oz in sec.sec	0.02100
Armature Inductance	L	micro henry	<100.0
Temperature Coeff of KE	C	%/deg C rise	-0.02
Number of Commutator Bars	Z		141
Number of Poles of Magnetic Field	PF		8
Motor Constants: Derived (at 25 Deg C)			
Mechanical Time Constant without Load	TM	millisec	2.88
Electrical Time Constant	TE	millisec	<0.16
Speed Regulation at Constant Term Voltage	RM	rpm/oz in	1.31

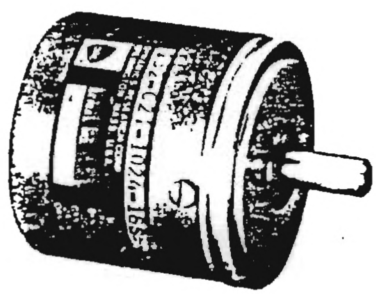
C. Characteristics for PMI U12 M4H Motor

Thermal Resistance	Symbol	Units	U12M4H
Mounted on Alum Heat Sink (8" x 16" x 3/8")			
Armature to Ambient at Stall	RAA	Deg C/Watt	1.90
Armature to Ambient at 3000 rpm	RAA	Deg C/Watt	1.27
Forced through air cooled			
Arm to AMB with Air Flow of .4 lbs/min	RAA	Deg C/Watt	0.80
Arm to AMB with Air Flow of .8 lbs/min	RAA	Deg C/Watt	0.51
Arm to AMB with Air Flow of 2.0 lbs/min	RAA	Deg C/Watt	0.26
Physical Characteristics			
Motor Diameter	D	in	5.50
Motor Length	LG	in	2.78
Motor Weight	W	lbs	11.00

Dynamics Research Corporation

MODEL 150/152

Incremental Optical Rotary Encoder



ACTUAL SIZE

- Our lowest cost rotary encoder
- Single LED light source
- Up to 4,096 counts per shaft revolution
- Sealed bearings available for maximum reliability

The Model 150/152 is a compact incremental, optical rotary encoder for light industrial applications. The 150/152 is available with discs having up to 1024 cycles per shaft revolution to provide a maximum of 4096 counts per revolution utilizing external 4X circuitry. This encoder is available with either differential sinewave or TTL compatible complementary square-wave outputs. Custom electronics can be provided to maximize encoder performance to best suit your application. The 150/152's small diameter (1.625") is appropriate for many limited size applications. In its standard configuration the unit can be used in applications where a low cost, easy to install, totally enclosed optical encoder is required. Typical applications include machine tools, assembly machinery, phototypesetters, and robotics.

SPECIFICATIONS

ELECTRICAL

Resolution:	• To 1024 cycles per shaft revolution (to 4096 counts per revolution with external 4X circuitry)
Light source:	• Gallium Arsenide LED rated for 100,000 hours MTBF (manufacturers specification)
Light sensors:	• Photovoltaic cells
Input power:	• 5 vdc (± 5%) at 125 ma (maximum)
Output format:	• Two count channel outputs (A and B) in phase quadrature with an optional zero reference (ZR) output
Quadrature specification:	• 90° ±30° (at 10 KHz output frequency)
Symmetry specification:	• 180° ±10° (at 10 KHz output frequency)
Rise and fall times:	• 1 µsec (maximum) into 1000 pf load capacitance
Frequency response:	• 40 KHz for count channels
	• 10 KHz for zero reference (stated as a function of count channel output frequency).
Zero reference angular width:	• 1 ± 1/2 count channel cycle.
Zero reference alignment:	• There is no specified alignment between the ZR and count channels.
Phase sense:	• Channel A leads Channel B for clockwise rotation of the shaft as viewed from the shaft end of the unit.
Pin connections:	• See Table 1
Outputs:	
Waveform:	**Signal levels:**
Sinewave (See Figure 1)	• Count channels: Differential sinewave outputs with amplitudes of 30 mv p-p (minimum) into a 2KΩ load at 40 KHz output frequency or 3,000 RPM whichever occurs first. DC offset is ±10% of p-p signal output maximum.
	• Zero reference: 20mv (minimum) usable signal level into a 2KΩ load at 10 KHz count channel output frequency.
Squarewave (See Figure 2)	• TTL compatible complementary outputs, from a 7404 output stage providing 16 ma sink current
Output options:	• Reversed phase sense — Channel B leads Channel A for clockwise rotation
	• Photo transistor light sensors available.
	• Custom electronics can be provided for a non-recurring charge.

MECHANICAL

Outline dimensions:	• See Figure 3
Shaft loading:	• 5 lbs. axially and radially (maximum)
Shaft radial runout:	• .001" T.I.R.
Starting torque at 25°C:	• Models with shielded bearings: 0.1 oz.-in. (maximum)
	• Models with sealed bearings: 0.5 oz.-in. (maximum)
Shaft angular acceleration:	• 10^6 radians/sec^2 (maximum)
Moment of inertia:	• 1.0 x 10^{-4} oz.-in.-sec.^{2} (maximum)
Bearing type:	• ABEC Class 5 (sealed or shielded)
Bearing life:	• 1 x 10^9 revolutions at full load (manufacturers specifications)
Shaft material:	• 303 series stainless steel
Slew speed:	• 5,000 RPM
Maximum operating speed:	• 3000 RPM or 40 KHz output frequency, whichever occurs first
Weight:	• 6 oz. (maximum)
Error:	• ±0.5 bits maximum (based on 4X cycle interpolation)
Connector:	• Not supplied on standard units

ENVIRONMENTAL

Operating temperature:	• 0° to +70°C
Storage temperature:	• -25° to +90°C
Shock:	• 10G's for 11 msec.
Vibration:	• 20 Hz to 2000 Hz at 5G's
Humidity:	• to 98% R.H. (non-condensing)

FIGURE 1

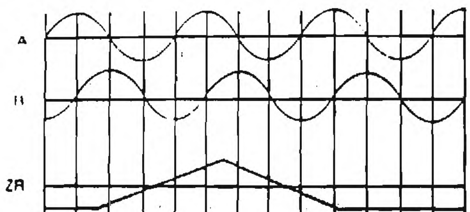


FIGURE 2

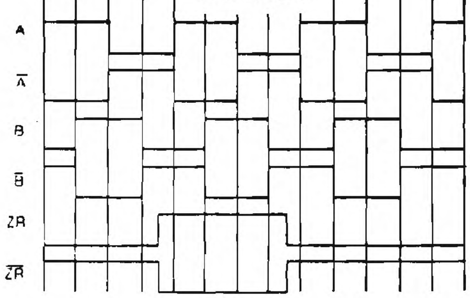


TABLE 1		
WIRE DESIGNATIONS FOR MODELS 150/152		
Function	Model 150 Sinewave Output	Model 152 Squarewave Output
Channel A	Orange	Brown
Channel $\overline{A}$	Green	Brown/White
Channel B	Yellow	Green
Channel $\overline{B}$	Blue	Green/White
Channel ZR	Gray	Orange
Channel $\overline{ZR}$	—	Orange/White
+5 Vdc	Red	Red
Ground	Black	Black

Warranty

DRC warrants its products against defects in materials and workmanship under normal and proper use and service for a period of one year from the initial date of shipment. The warranty period for products repaired or replaced during the first six months of the original one year warranty will extend to the expiration date of the original warranty. The warranty period for products repaired or replaced during the last six months of this initial one year new product warranty, and for products repaired or replaced after the expiration of this initial one year new product warranty, is limited to a period of six months from the date of shipment of the repaired or replaced unit.

This warranty does not apply to any product which has been operated at other than specified voltages or currents, or which has been subjected to abuse, or which has been disassembled or otherwise tampered with or altered.

DRC's obligation under this warranty is limited to, at DRC's election, furnishing without charge, F.O.B. Wilmington, Massachusetts, a replacement for any defective product or part, or repairing such product or part.

The foregoing warranty is exclusive of and in lieu of all other warranties, whether written, oral or implied.

HOW TO ORDER

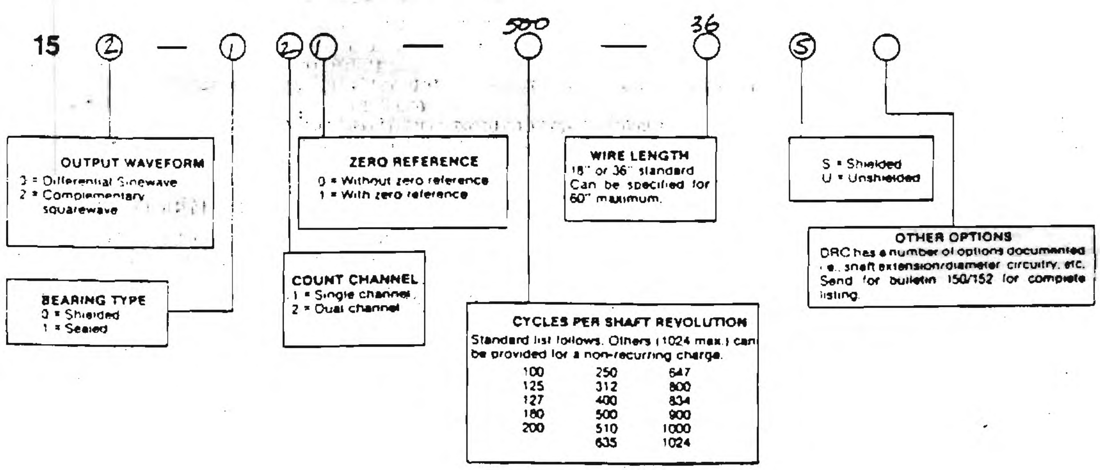
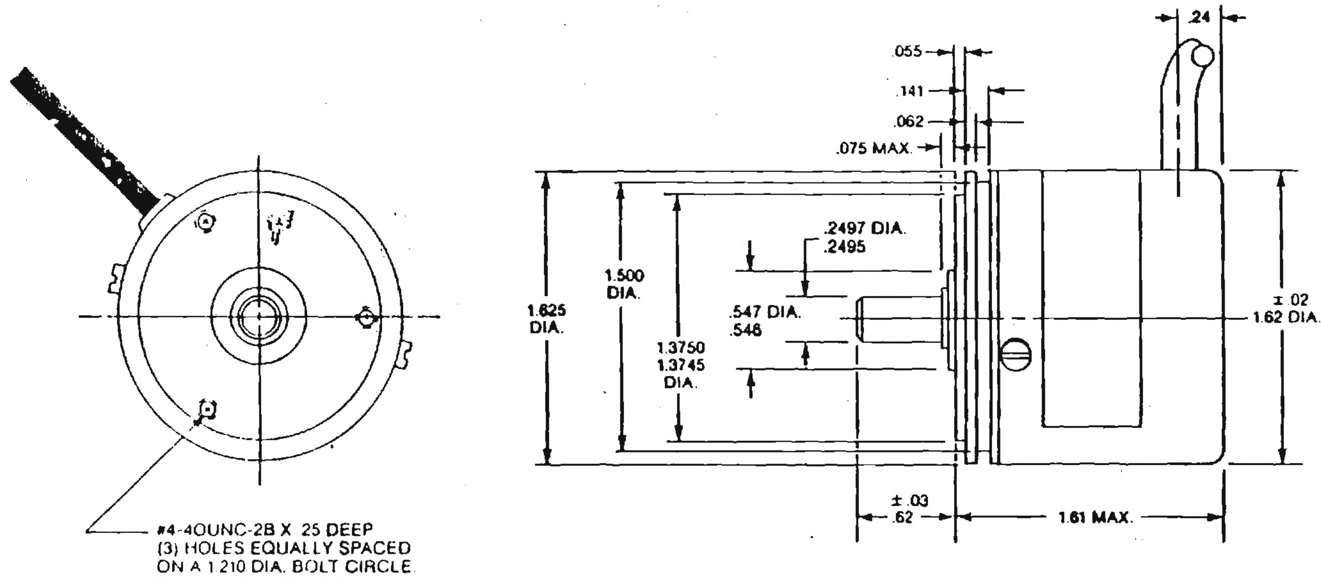


FIGURE 3



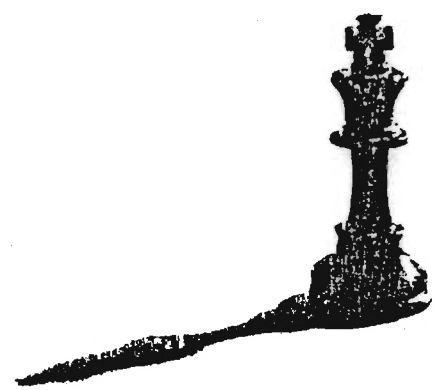
TOLERANCES	
.XX	±.01"
.XXX	±.005"

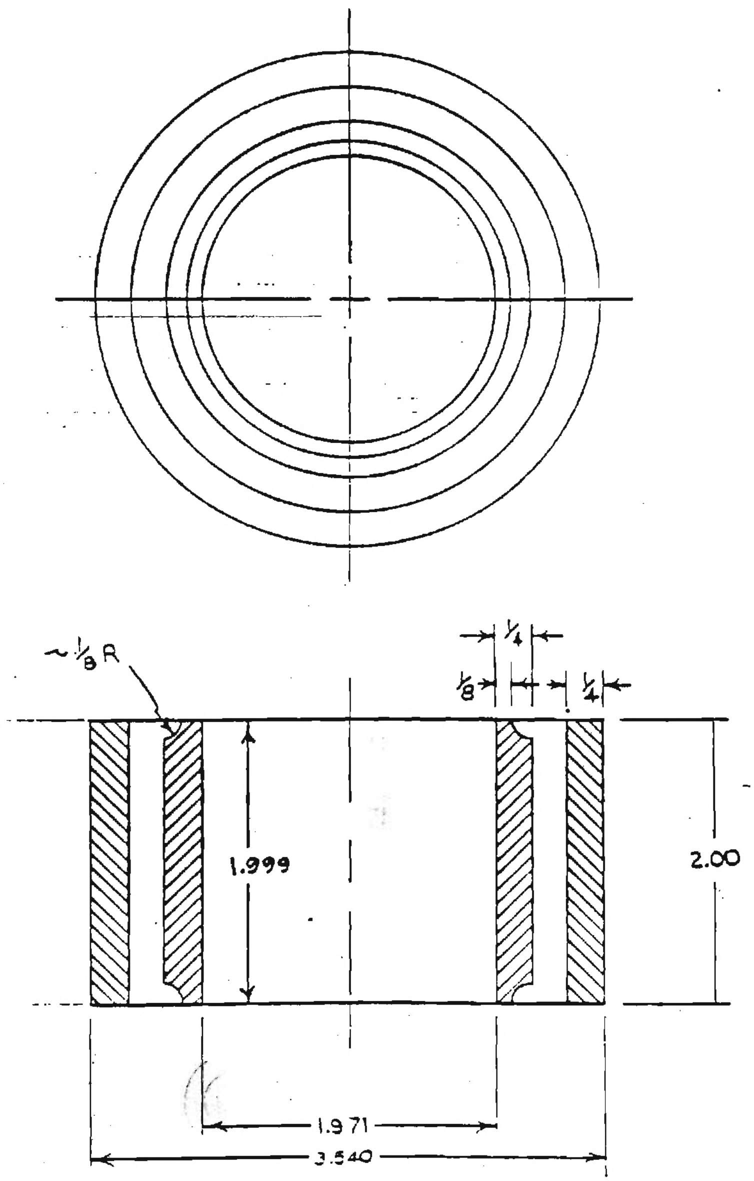
OPERATING CONSIDERATIONS:

The use of a flexible coupling is required between the encoder shaft and the drive shaft. Safeguards should be made to ensure the input voltage does not exceed specification. The use of 3 servo cleats are recommended when employing the servo mount option.

Dynamics Research Corporation

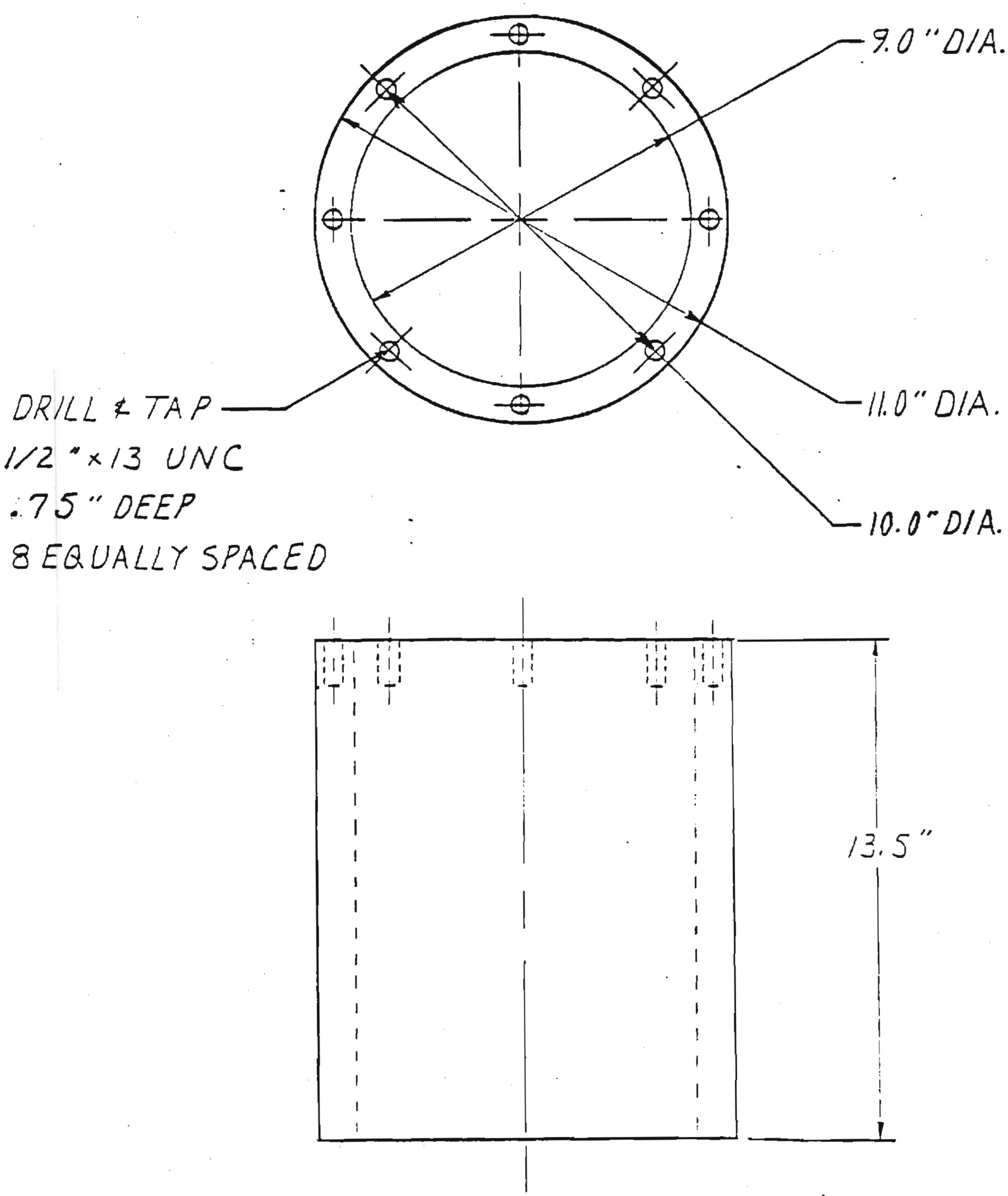
Encoder Division
60 Concord Street, Wilmington, MA 01887
Telephone (617) 658-6100/TWX: (710) 347-0299





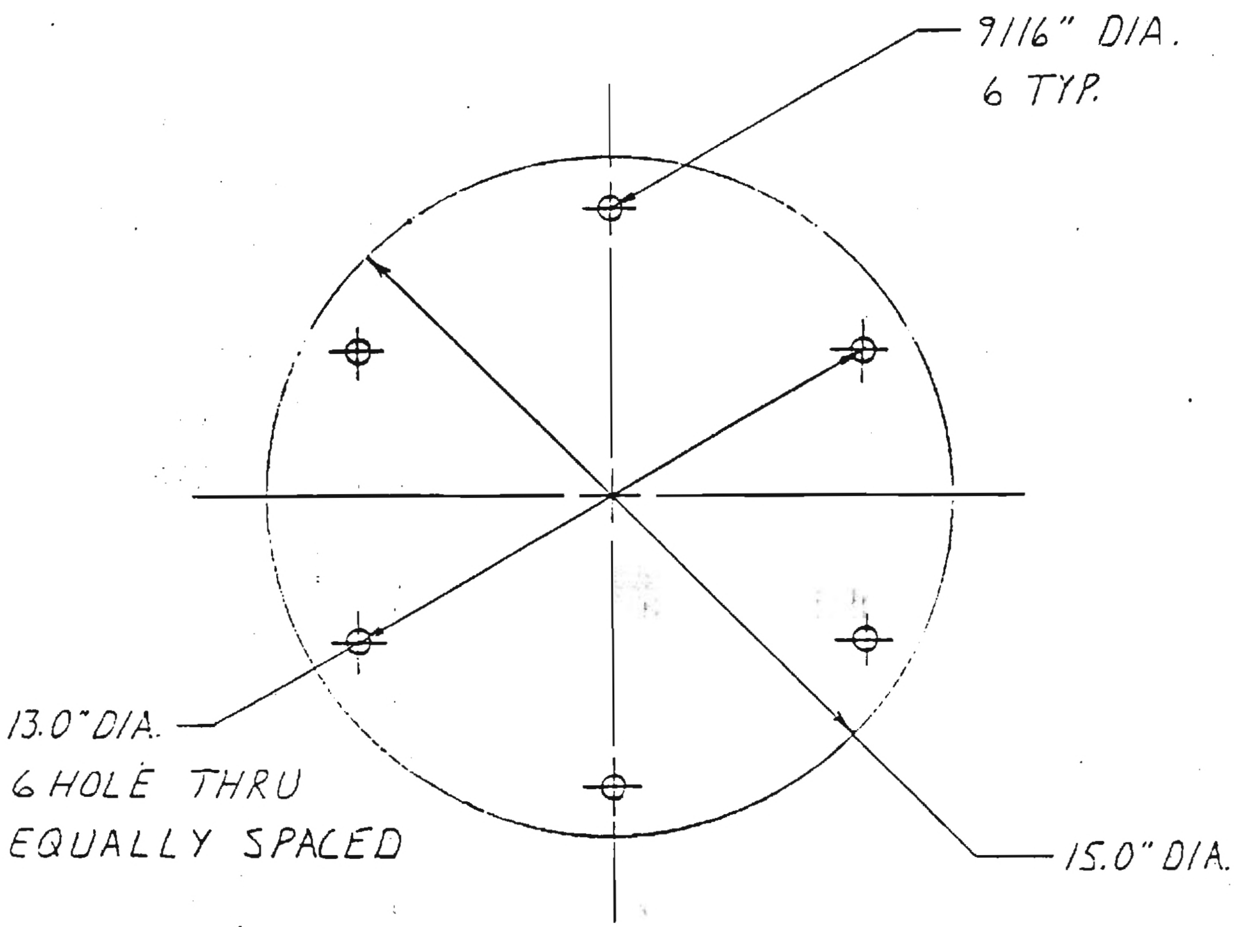
Bearing Spacers (steel)

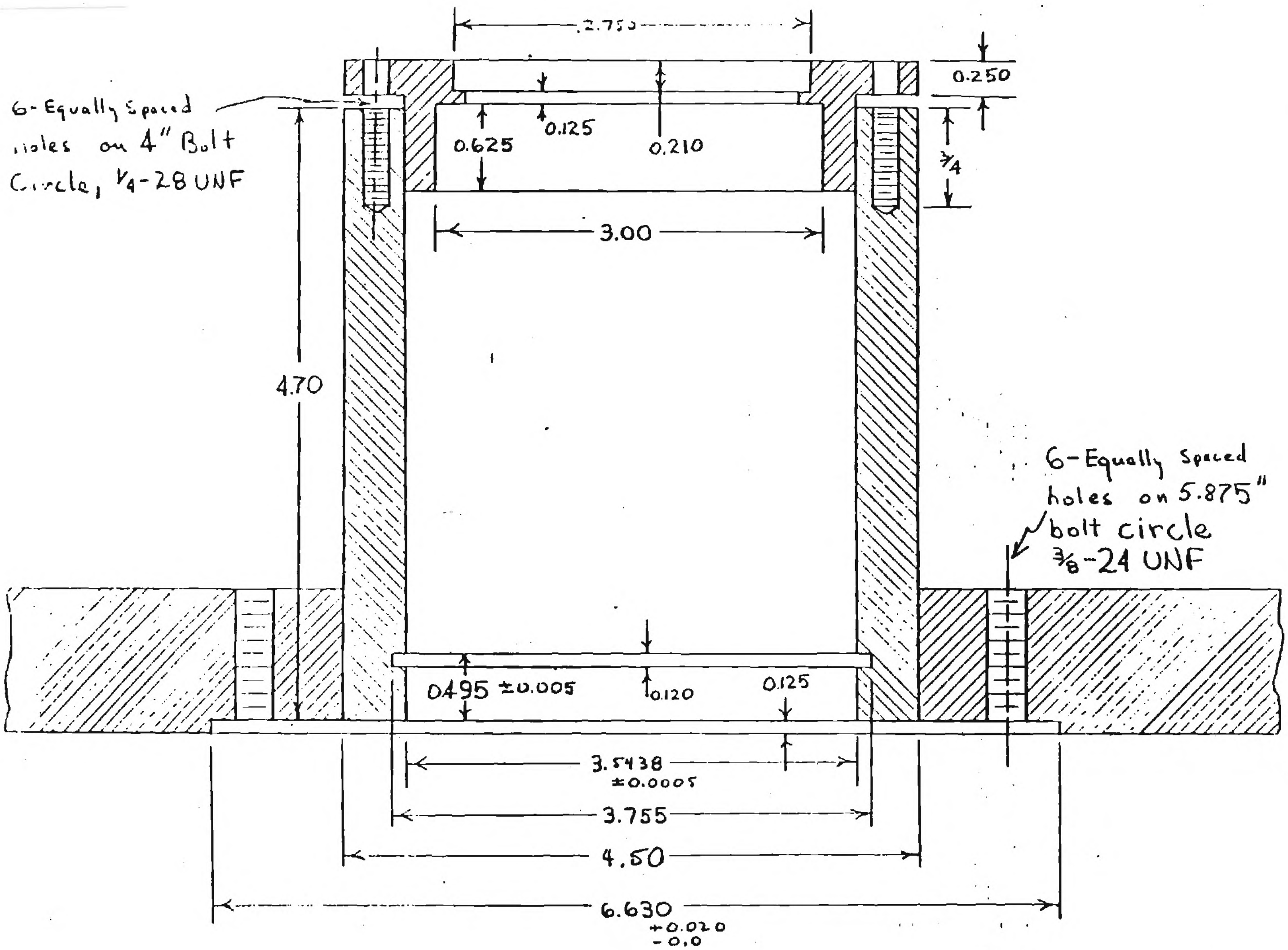
FLEXIBLE ARM-BASE SUPPORT, CARBON STEEL

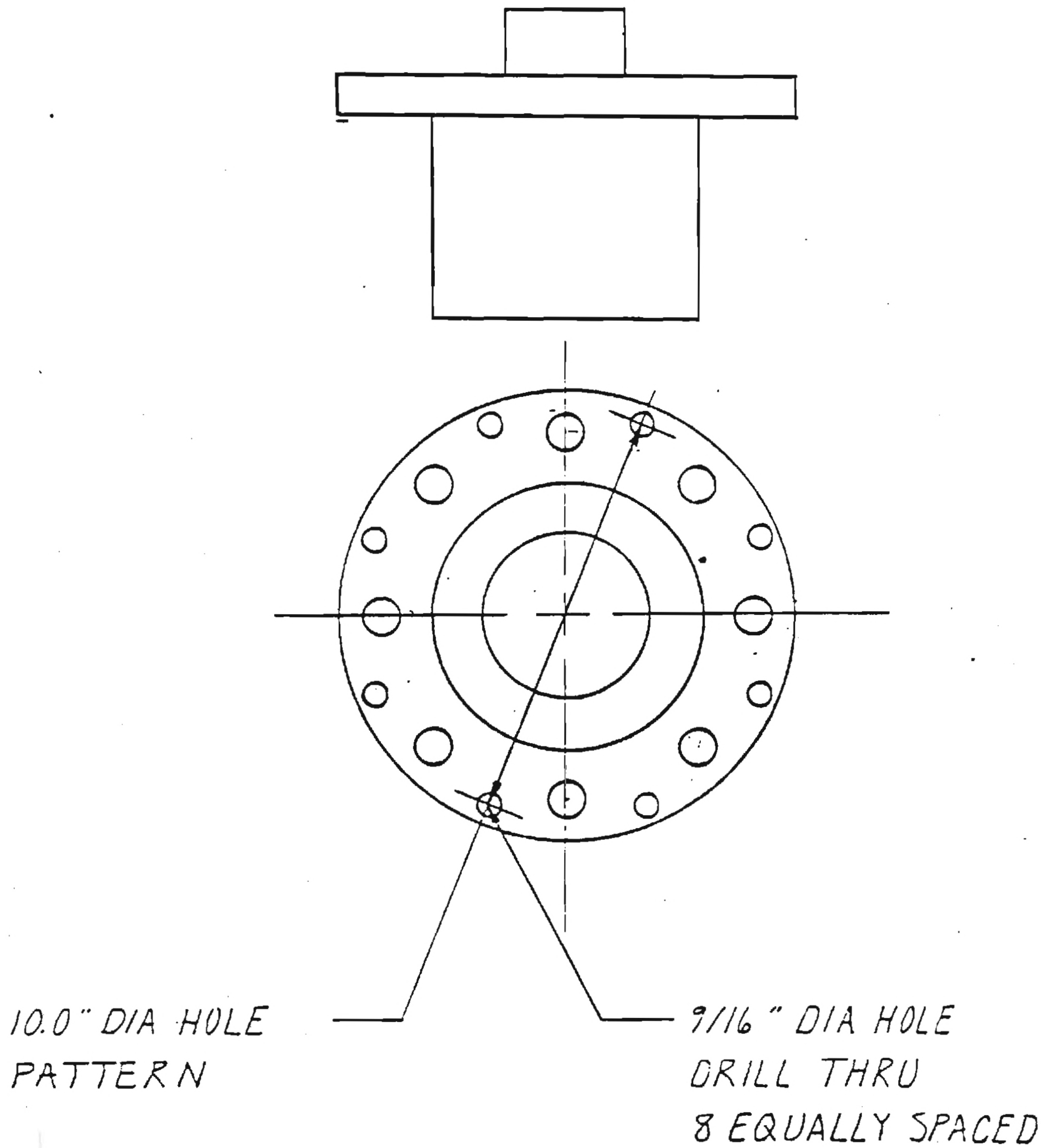


BASE PLATE

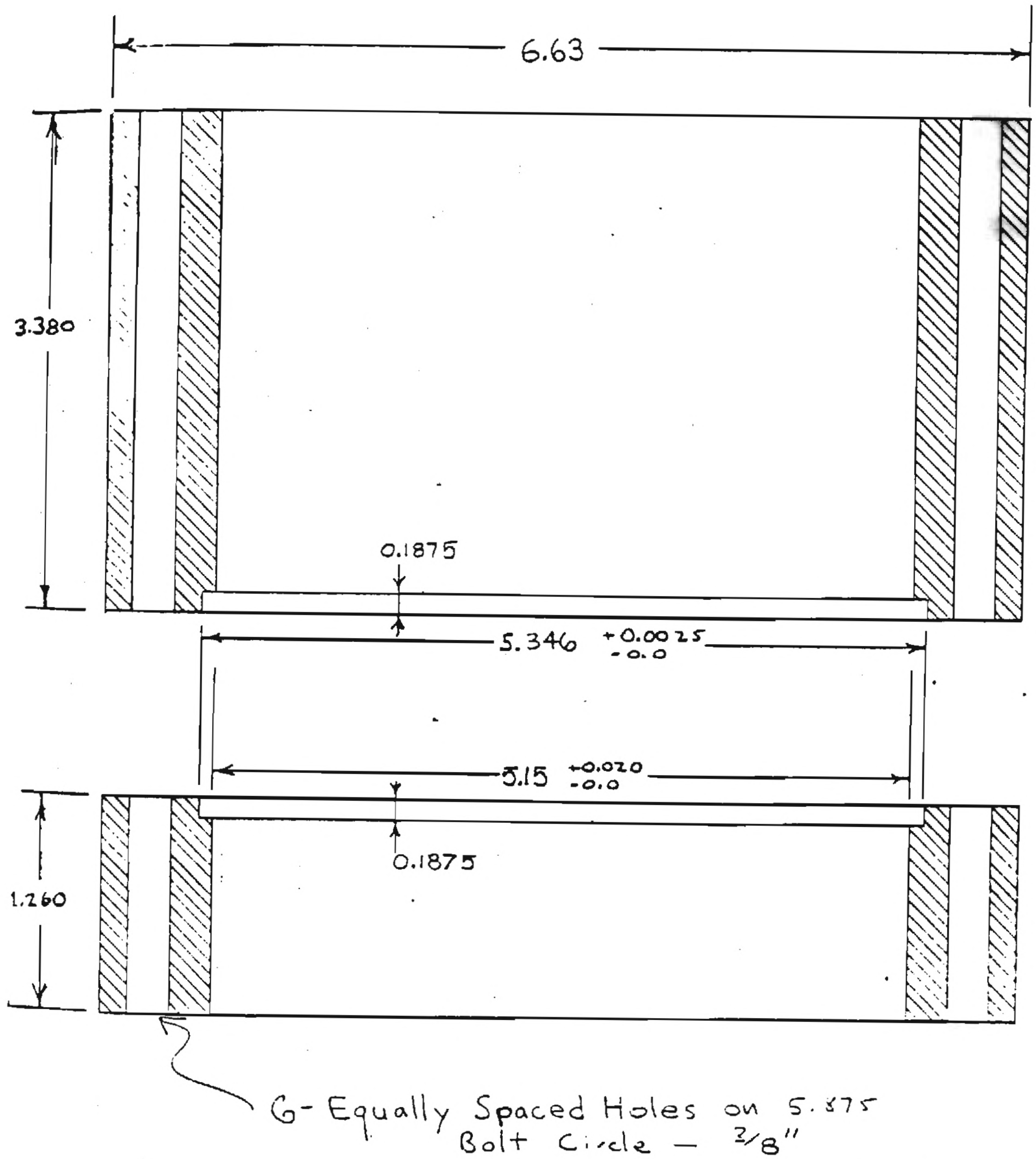
1/4" STEEL PLATE



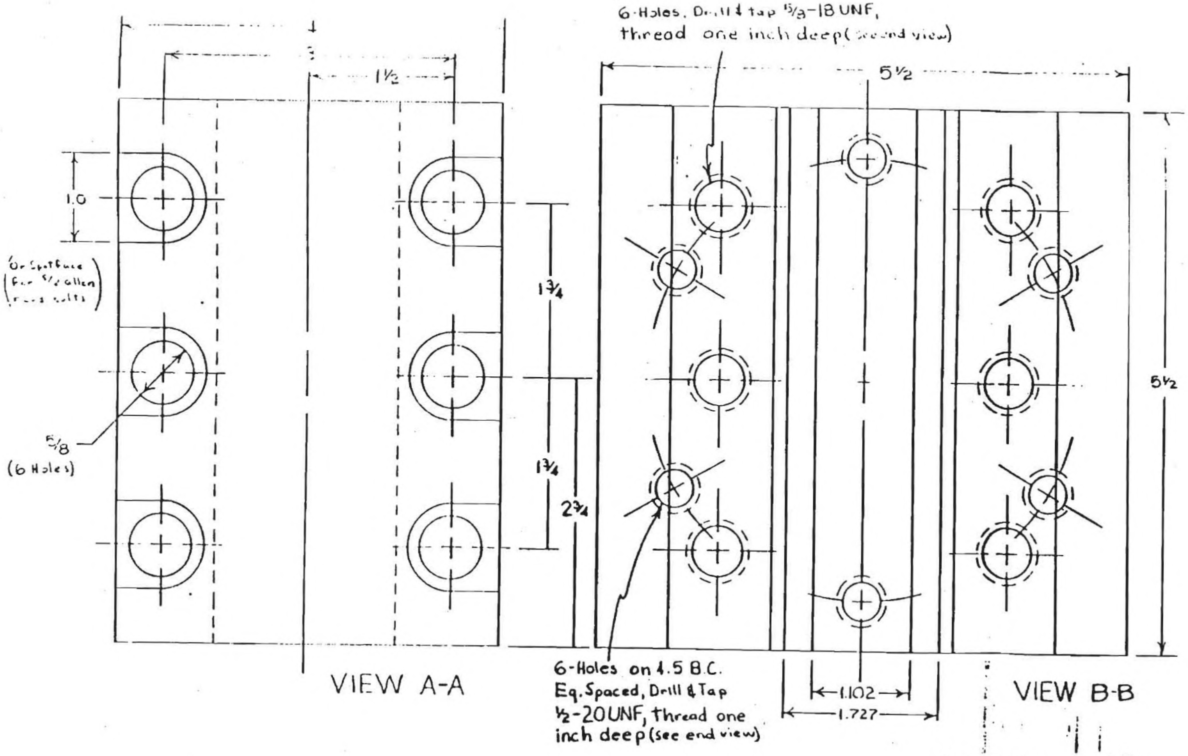

2.750
0.250
6-Equally Spaced holes on 4" Bolt Circle, 1/4-28 UNF
0.125
0.625
0.210
3/4
3.00
4.70
6-Equally Spaced holes on 5.875" bolt circle 3/8-24 UNF
0.495 ±0.005
0.120
0.125
3.5438 ±0.0005
3.755
4.50
6.630 +0.020 -0.0



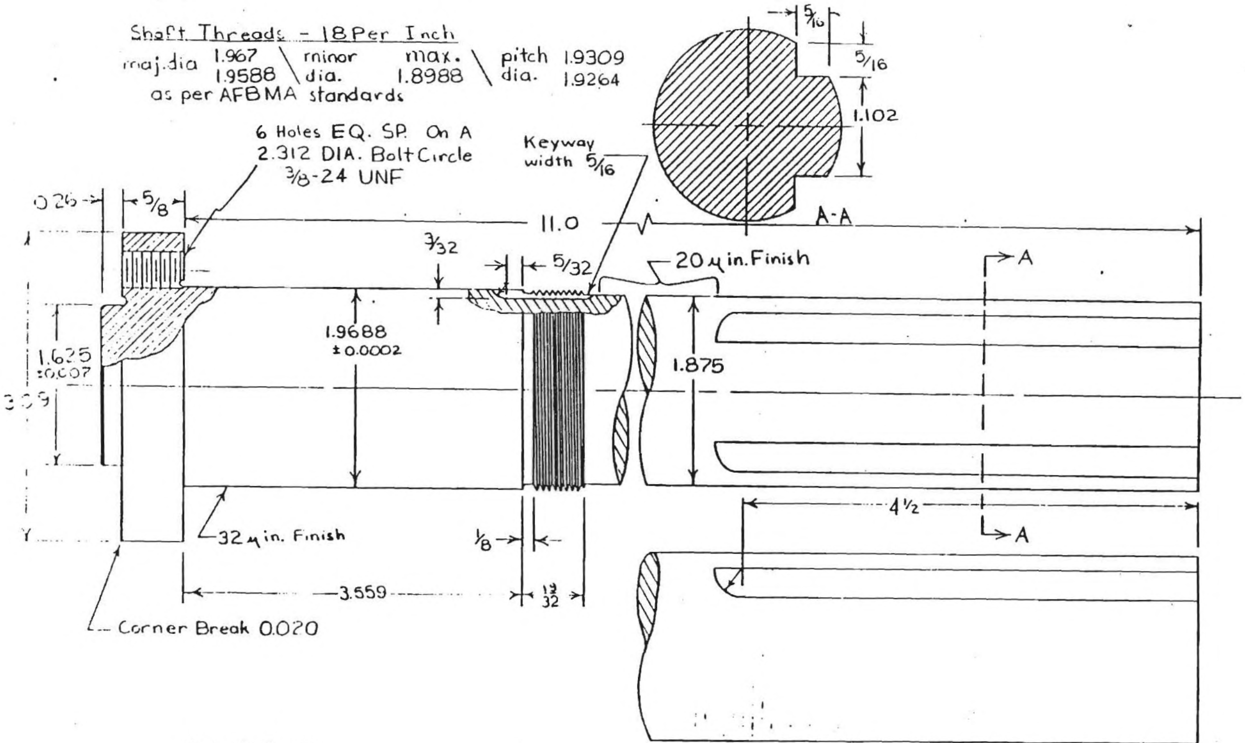
ADD THESE HOLES TO THE EXISTING
FLANGE / DRIVE ASSEMBLY.



<u>Harmonic Drive Housing Tubes</u> (Alum.)

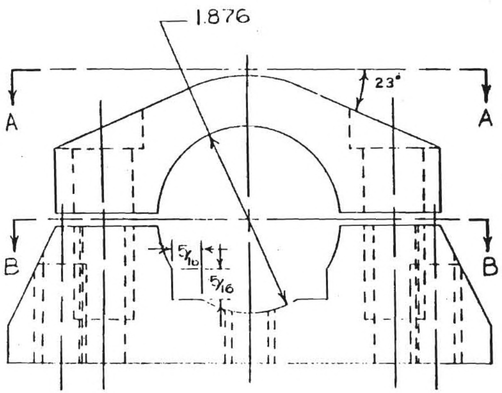


Output Hub Drwg #2

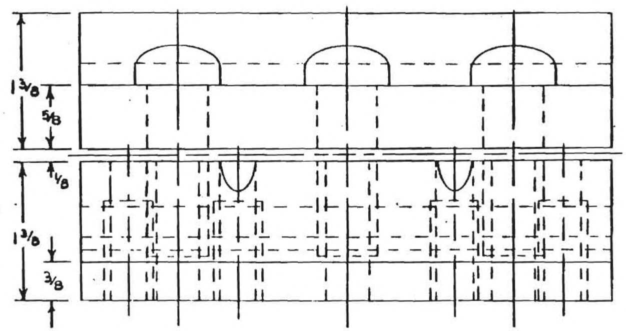


Output Shaft

5-12-84

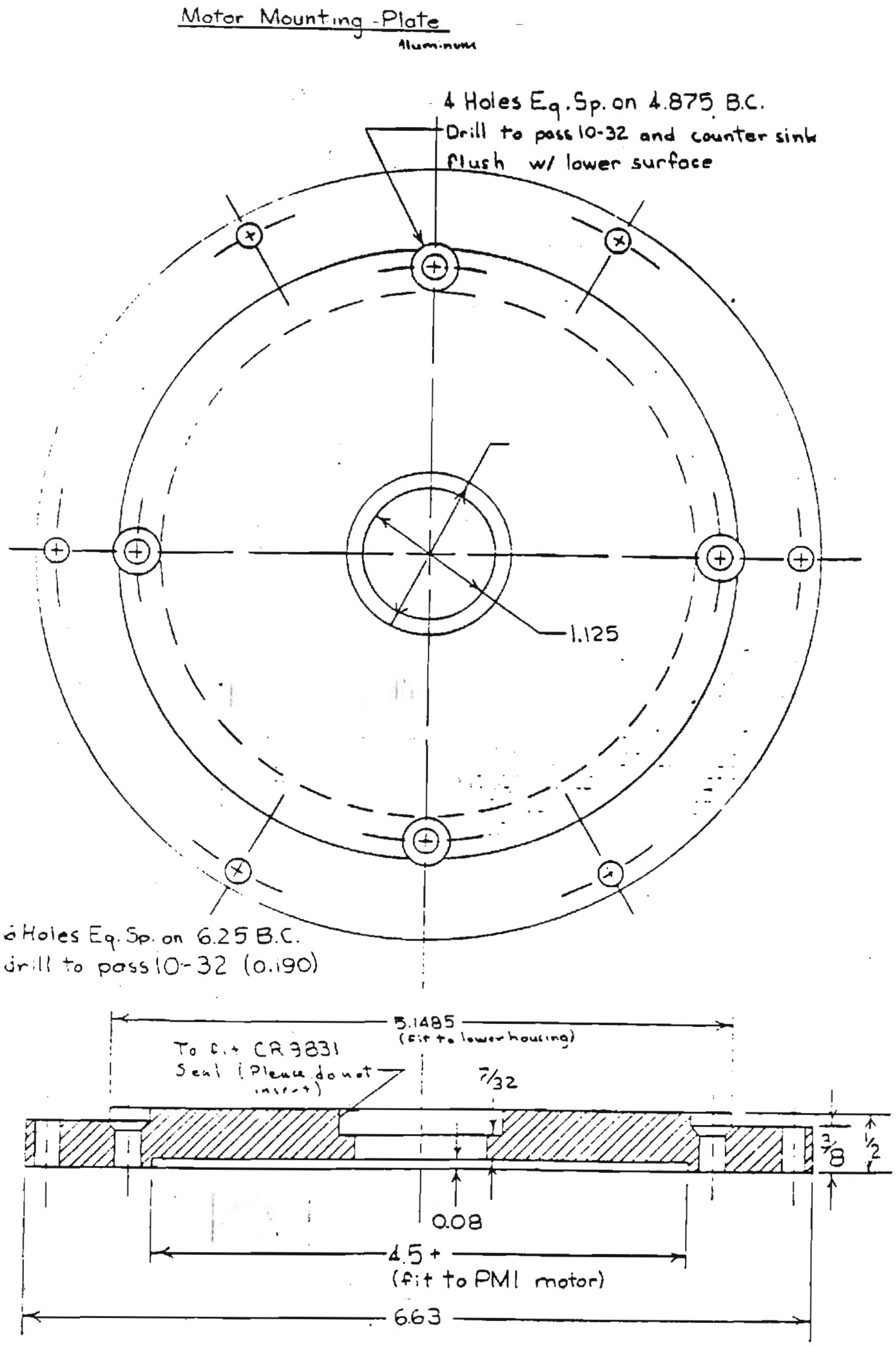


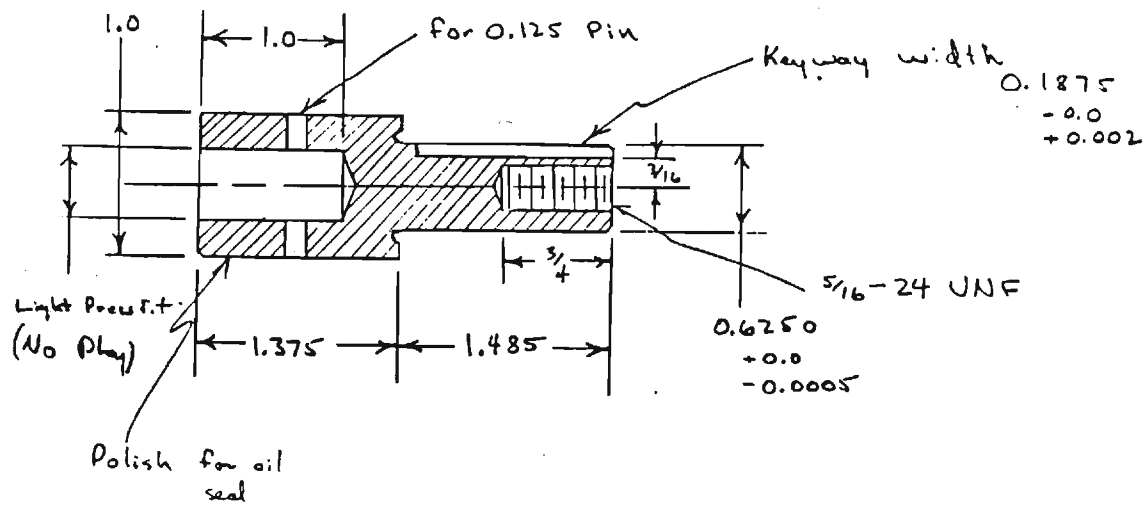
End View



Side View

5-84 Output Hub Drwg #1


Motor Mounting Plate
Aluminum
4 Holes Eq. Sp. on 4.875 B.C.
Drill to pass 10-32 and counter sink
flush w/ lower surface
1.125
6 Holes Eq. Sp. on 6.25 B.C.
drill to pass 10-32 (0.190)
5.1485
(fit to lower housing)
To fit CR 9831
Seal (Please do not insert)
7/32
3/8
1/2
0.08
4.5 +
(fit to PMI motor)
6.63



Motor Shaft Extension/Adapter

1030 C.R. Steel

Appendix B

VERTICAL DRIVE ASSEMBLY

LRW 20 Linear Motion Unit, p. 72

Mechanical Drawings, p. 76

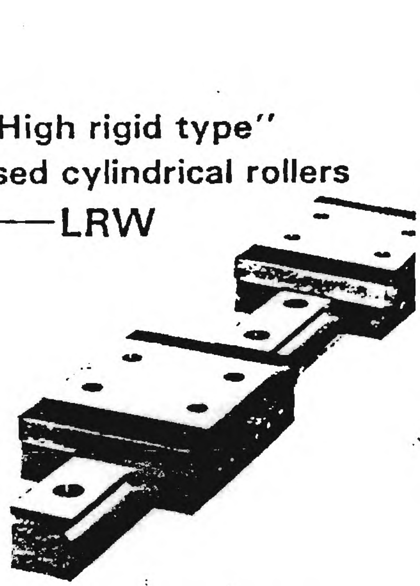
(See Fig. 3, p. 9 for photograph of assembly)

VERTICAL DRIVE ASSEMBLY

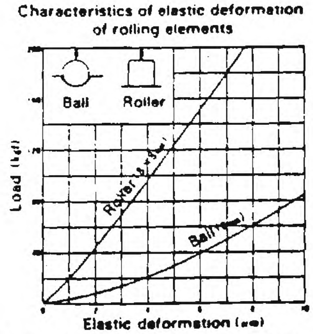
MOTOR:	MAVILOR MT80 torque: 4.3 in.-lb. at 1500 rpm
ENCODER:	500 ppr
TACH:	10 V per krpm
OUTPUT MEMBER:	SAGINAW BALL SCREW & LRW20 LINEAR ROLLER WAY
SPEED REDUCTION:	2.0 : 1 BETWEEN MOTOR AND BALL SCREW VIA TIMING BELT DRIVE
RANGE OF MOTION:	5.0 in. (WITH LIMIT SWITCH AND STOP PLATE)

LINEAR ROLLER WAY

"High rigid type" used cylindrical rollers ——LRW



Characteristics of elastic deformation of rolling elements



* This graph shows elastic deformations of steel ball and cylindrical roller under same condition. For example, when load 40 kgf is applied, steel ball deforms 6 μm, but cylindrical roller elastically deforms only 1.8 μm.

IKO Linear Roller Way is a the world's first endless linear motion bearing unit to use rollers rather than balls as the rolling elements. **IKO** Linear Roller Way is highly rigid and stable, and provides certain linear transportation and outstanding precision while subjected to loads in all directions and moment.

IKO Linear Roller Way is especially stable since elastic deformation of bearing assembly is very little even if a heavy load or a fluctuating load is applied. Therefore, this is suitable for heavy duty machine tools with vibration/shock such as heavy duty machining center, milling, cutting, punching and grinding machines, industrial robot and other linearly moving mechanisms which require high precision.

Structure and Features

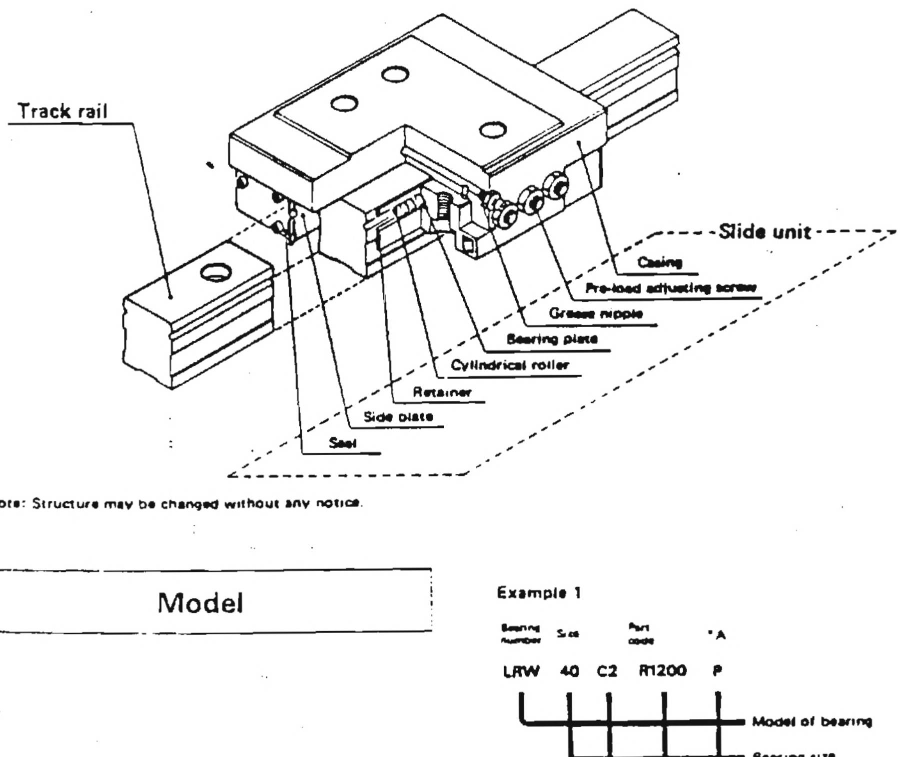
IKO Linear Roller Way consists of one or several "slide units" and a "track rail". In the slide unit, following parts are compactly incorporated; cylindrical rollers, bearing plates, side plates, seals, grease nipple, retainers, etc. (See Fig. 1)

Two rows cylindrical rollers incorporated in a slide unit are arranged alternately cross to each other. Therefore, elastic deformation at rolling contact area is very little even if loads in every direction are applied, and stable operating accuracies and high rigidity are obtainable under loads fluctuating in magnitude and/or direction.

Further, **IKO** Linear Roller Way can be used without further adjustment of pre-load, since it has been properly adjusted at the factory. If the pre-load has to be finely adjusted or re-adjusted after long operation, it is easily done with the pre-load adjusting screws on the side of the slide unit.

The side units can be easily fixed, either by tightening the bolts in the female threads of the machine from the bottom of the slide unit, or inversely, by tightening the bolts in the female threads of the slide unit from the machine.

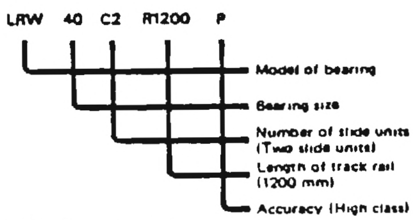
Fig. 1 Structure of Linear Roller Way



Note: Structure may be changed without any notice.

Model

Example 1

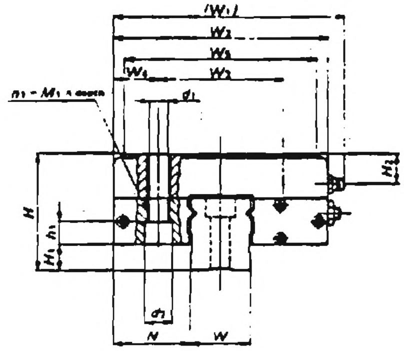


*A: Classification symbol

Bearing number

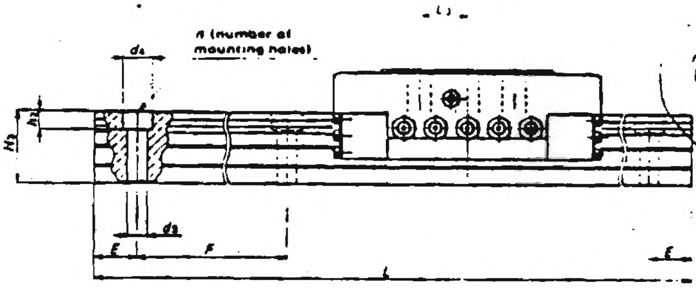
The bearing number of IKO Linear Roller Way consists of a model code, size, part code, pre-load symbol, classification symbol and supplemental code as shown next.

LINEAR ROLLER WAY



Bearing number	Dimensions of assembly mm			Dimensions of slide unit mm													
	H	H_1	N	W_1	W_2	W_3	W_4	W_5	L_1	L_2	L_3	L_4	d_1	d_2	h_1	$n_1-M_1\times_{depth}$	H_2
LRW 20	35	8	25	80	70	40	15	84	105	24	—	70	8.8	11	8	4−M 8×10	6
LRW 30	48	13	32	102	92	56	18	86	122	30	—	76	8.6	14	9	4−M10×12	7
LRW 40	60	13	42	132	122	76	23	112	158	48	—	100	10.6	17	14	4−M12×13	12
LRW 50	70	15	52	162	152	96	28	142	212	72	—	146	12.5	19	17	4−M14×15	13
LRW 60	85	17	62	190	180	110	35	170	256	100	50	170	12.5	19	19	6−M14×18	20

Note(1): The values T_x and T_y are the ones for static rated torque for two slide units and the direction is as shown in Figs. 3.1 and 3.2 of page 5.



= 1 kgf·m

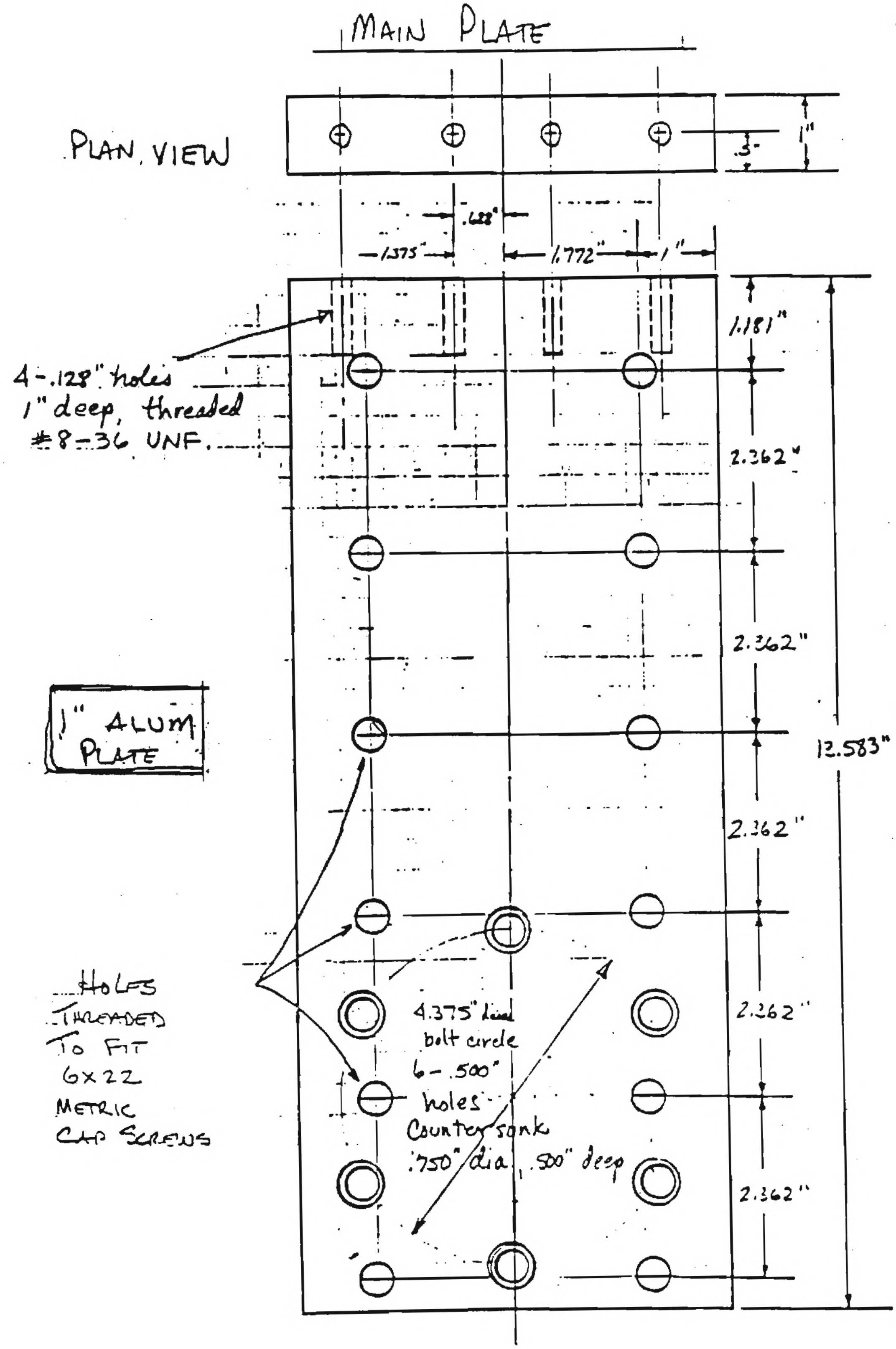
Dimensions of track rail mm								[illegible]	[illegible]	[illegible]	Static rated moment			
W	H_3	L (n)	d_3	d_4	h_2	E	F	M×ℓ	C kgf	Co kgf	To kgf·m	Tx(¹) kgf·m	Ty(¹) kgf·m	Weight
20	23	480(8) 660(11) 840(14) 1020(17) 1200(20) 1500(25)	7	11	9	30	60	M 6×22	1 740	2 200	24 6	173	160	1.5 Kg
28	34	480(8) 660(11) 840(14) 1020(17) 1200(20) 1500(25)	9	14	12	30	60	M 8×35	3 200	4 110	62.9	383	351	
38	40	800(10) 1040(13) 1200(15) 1520(19) 1920(24)	14	20	16	40	80	M12×40	5 880	8 070	165	972	888	
48	47	800(8) 1000(10) 1200(12) 1500(15) 2000(20) 3000(30)	16	23	19	50	100	M14×50	9 960	15 300	395	2 420	2 230	
58	54	840(7) 1200(10) 1560(13) 1920(16) 3000(25)	18	26	21	60	120	M16×55	14 000	22 100	668	4 210	3 880	

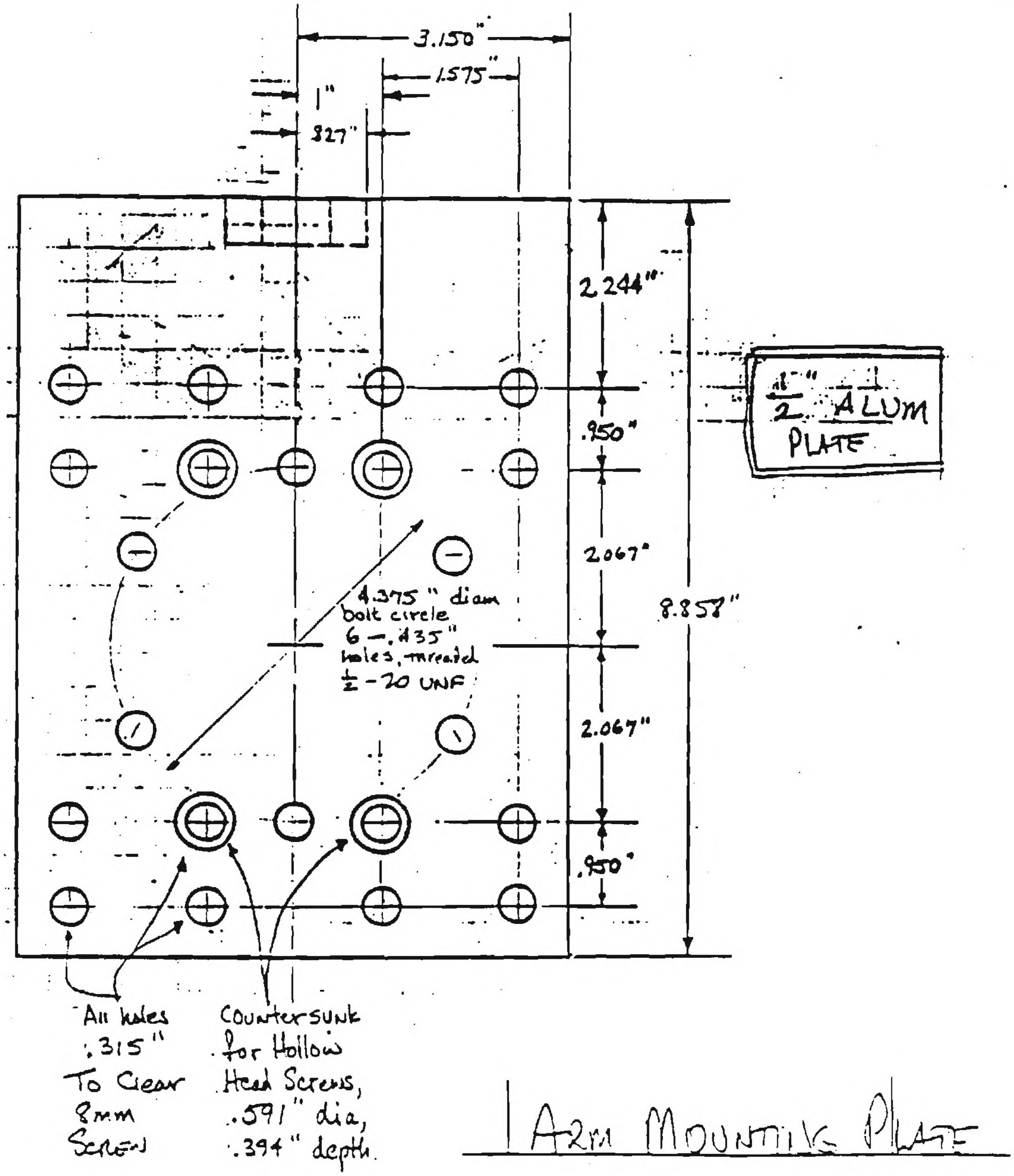
6 mm screws

LRW20 rail 3.39 Kg/m

Approx cost $ 340

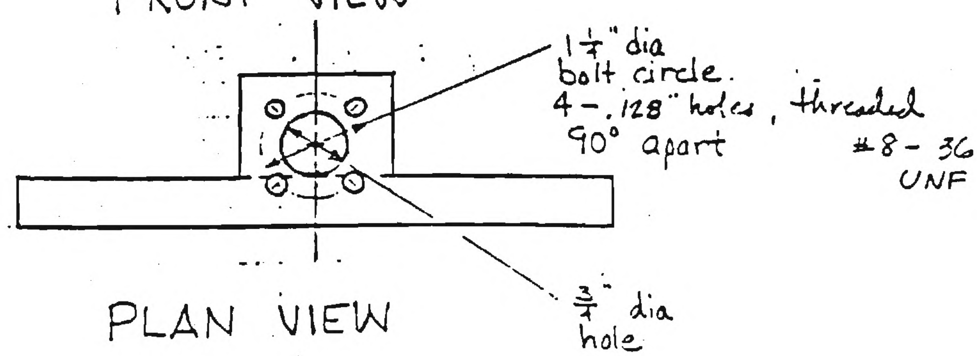
OK → LRW20 C2 R360 H suggestion


MAIN PLATE
PLAN VIEW
.3"
1"
.688"
1.375"
1.772"
1"
1.181"
4-.128" holes 1" deep, threaded #8-36 UNF.
2.362"
2.362"
1" ALUM PLATE
12.583"
2.362"
2.262"
2.362"
HOLES THREADED TO FIT 6X22 METRIC CAP SCREWS
4.375" dia bolt circle
6-.500" holes
Countersink .750" dia, .500" deep



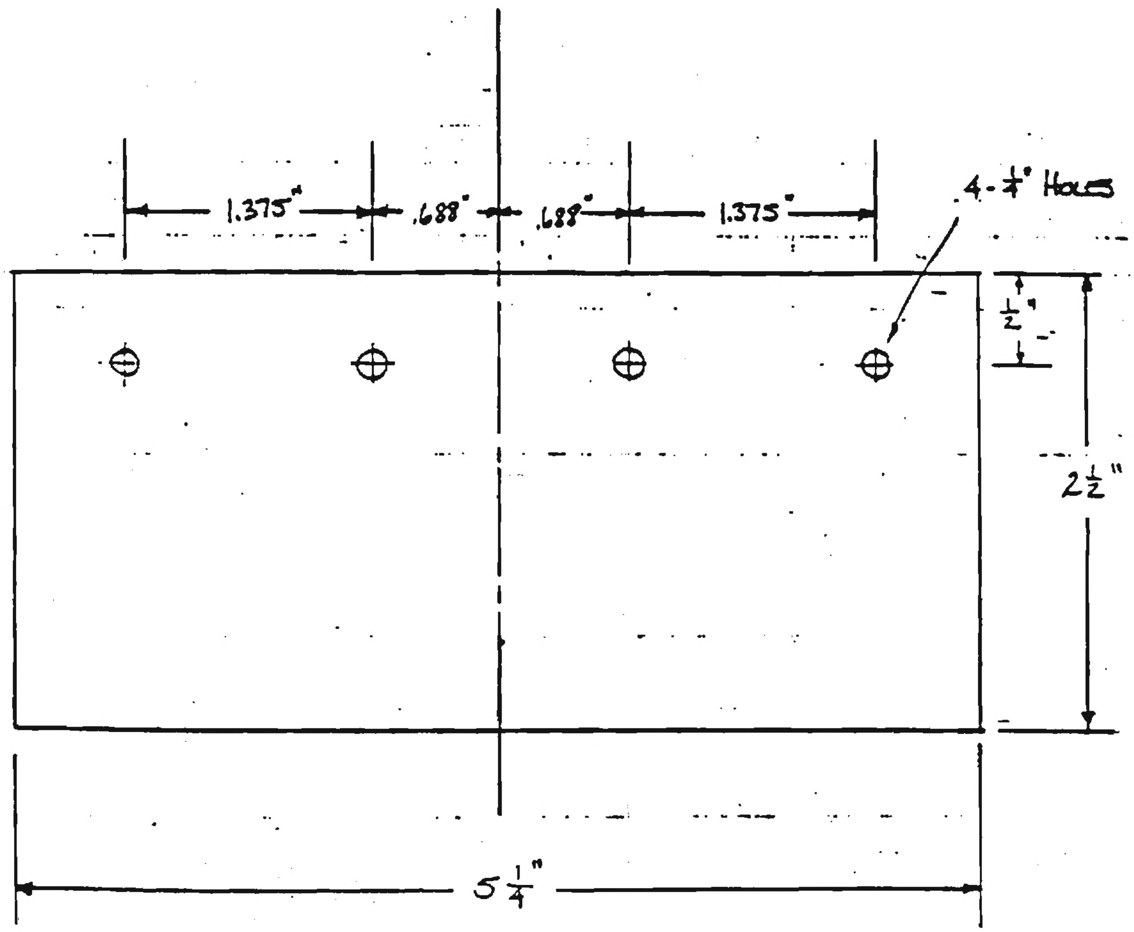
Arm Mounting Plate

FRONT VIEW



PLAN VIEW

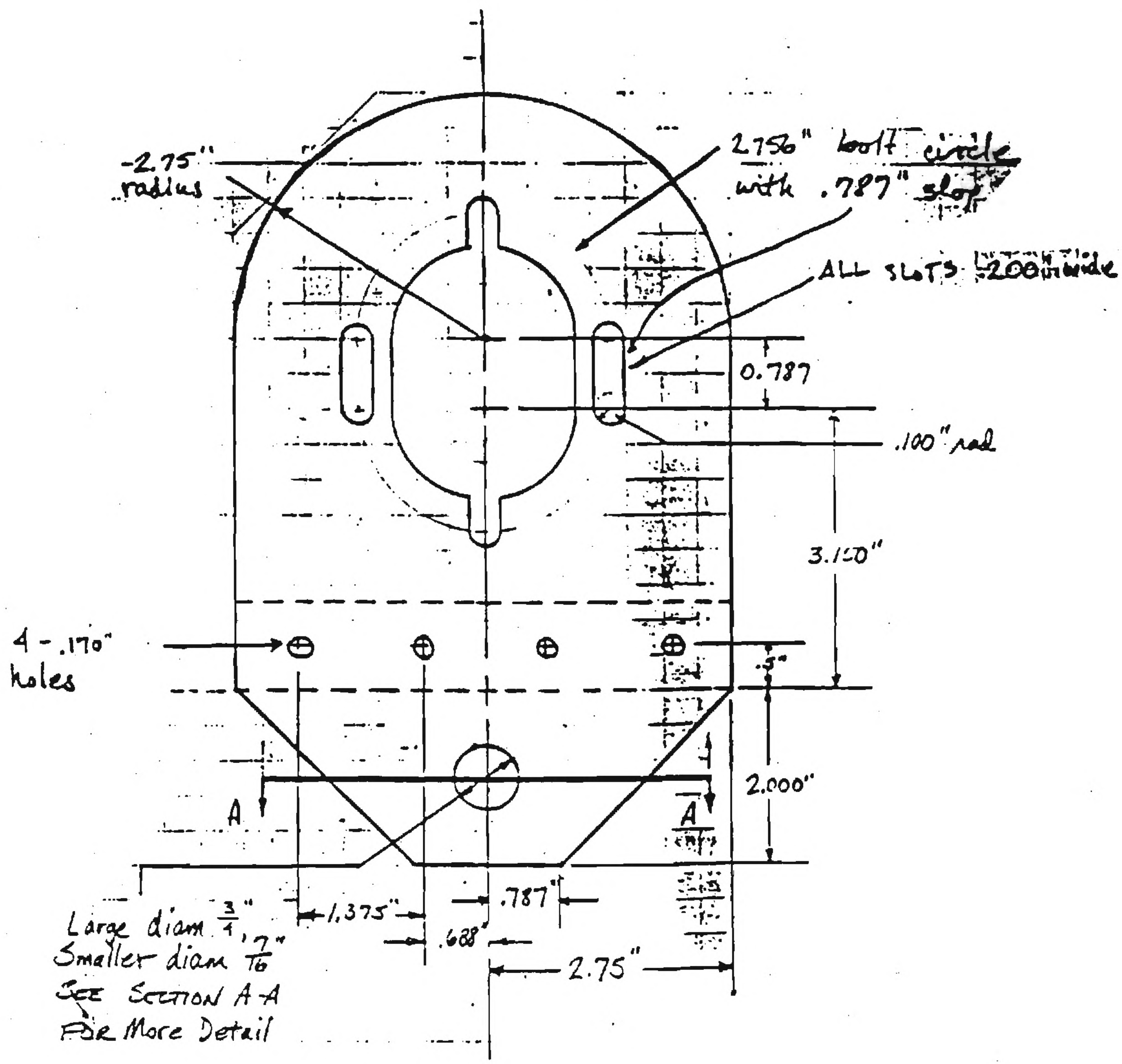
STOP PLATE



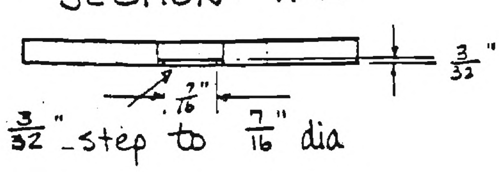
1/4" ALUM PLATE

FRONT PLATE MODIFICATION
DRILL AND TAP 4 HOLES, SAME PATTERN AS ABOVE, 1/2" FROM FRONT SURFACE, TO ACCEPT 8 × 32 UNF SCREWS. MAKE HOLES 1" DEEP.

TOP PLATE



SECTION A-A



Appendix C

ELBOW JOINT ASSEMBLY

(See Fig. 4, p. 12 for exploded view of assembly)

ELBOW JOINT

MOTOR:	MAVILOR MT 80
ENCODER:	500 ppr
TACH:	10 V per krpm
SPEED REDUCTION:	HDC 4M-200 HARMONIC DRIVE, 200 : 1 RATIO
JOINT OFFSET:	4.0 in.
RANGE OF MOTION:	-15° to +180° CLOCKWISE FROM FULLY EXTENDED POSITION

WEIGHT REDUCTION

EXAMPLE: ELBOW JOINT

- TARGET WEIGHT - 33.07 lbs.
- PROTOTYPE WEIGHT - 35.80 lbs.
- FEASIBLE WEIGHT - 27.0 lbs.

INFRANOR INC

MAVILOR®
DC Servo Motors

MO/MT Series Servo Motors
and Servo Motor Systems

Tachometer Option

This tachometer, specifically designed for integration into Mavilor Motors, has a very low inertia and low ripple assuring optimum performance.

Characteristics

Voltage constant, V/krpm	10
Voltage ripple, %	1.5
Voltage linearity at 3600 rpm, %	0.15
Bidirectional tolerance, %	0.10
Temperature coefficient, %/°C	−0.02
Inertia, oz-in.sec²	3.77×10^{-3}
Armature resistance, ohms	98.4
Inductance, mH	30
Current, mA	5
Maximum current, mA	30
Maximum velocity, rpm	6000
Armature weight, oz	4.8
Stator weight, oz	8.3

MAVILOR High Torque MT Series

With almost twice the rated torque of an equivalent size in the MO series, the MT series motors have exceptionally high torque/weight ratios with ultra-low mechanical time constant. Output torque is maximized by incorporating higher strength magnets and increased ampere turns in the armature winding.

Intended for operation at 1,000 rpm, these motors allow for increased duty cycle for repetitive short move positioning and eliminate the need for gearing on positioning applications. Due to the lower mechanical time constant, they provide faster positioning, where the move distances are short. In low speed, high torque applications gearing can be eliminated.

Specifications @ 40°C Ambient

MODEL

MOTOR PARAMETERS	UNITS	MO7000	MO7001	MO7002	MO10000*	MT80	MT300	MT600	MT1000	MT2000	MT4500
Rated Speed	rpm	3000	3000	3000	3000	1500	1000	1000	1000	1000	1000
Rated Voltage (± 5%)	Vdc	212	179	142	237	79	122	135	165	165	161
Rated Current	amps	36	40	48	61	1.5	2.4	3.6	4.0	7.6	12.2
Rated Power Output	Watts	7050	6680	6260	13300	75	200	347	520	1000	1690
Efficiency	%	92.75	92.7	92.0	92	60	67	71	78.8	80	86
Rated Torque	in-lb.	199	188	177	375	4.3	17.8	30.1	43.5	86.7	146.0
Maximum Torque	in-lb.	CF	CF	CF	3009	28.1	95.0	180.5	283.6	587.5	866.2
Maximum Speed	rpm	CF	CF	CF	3200	2000	1250	1500	1200	1300	1300
EMF Constant (± 5%)	V/krpm	68.8	58.2	46.2	76.15	35.25	90	102	139	140	144.5
Torque Constant (± 5%)	in-lb./amp	5.83	4.91	3.88	6.38	2.98	7.61	8.62	11.74	11.83	12.21
Friction Torque	in-lb.				2.655	0.119	0.150	0.345	0.531	0.947	1.221
Damping Constant	in-lb./krpm				3.540	0.080	0.190	0.456	1.000	1.770	1.832
Terminal Resistance	ohms	0.195	0.166	0.100	0.100	14.5	10.5	6.88	4.76	2.43	0.97
Armature Inductance	µh	Technical specifications for MO7000 Series are preliminary. Infranor Applications Engineering should be consulted for definitive data of specification			100	2000	2300	2300	2800	1300	570
Inertia	oz-in.-s²				7.08	0.0064	0.065	0.124	0.340	0.850	1.416
Mechanical Time Constant	ms				16	5.5	6.24	6	6.2	7.8	4.86
Transitory Power	kW/sec.				2400	223	288	477	428	735	958
Thermal Time Constant[5]	sec.				390	90	312	240	336	384	336
Thermal Time Constant[6]	sec.				2250	1200	2400	2500	2700	3840	3120
Thermal Resistance[5]	°C/W				0.11	0.33	0.27	0.50	0.17	0.13	0.19
Thermal Resistance[6]	°C/W				0.03	0.73	0.50	0.35	0.25	0.20	0.15
Radial Load[4]	lb.				242	44	55	55	110	132	154
Axial Load	lb.				165	33	44	44	55	88	88
Weight	lb.	132	132	132	187	4.7	12.1	15.4	26.5	44.1	68.2

[1] Motor mounted to Al. heat sink sized

[2] For an S3 cycle of . sec. at 1% duty cycle

[3] Max. speed in cont. service. Short periods to .

[4] Radial load applied at midlength of shaft

[5] Rotor-to-housing

[6] Housing-to-ambient

* The Continuous rated characteristics for MO10000 are for force ventilated (105 cfm) conditions only

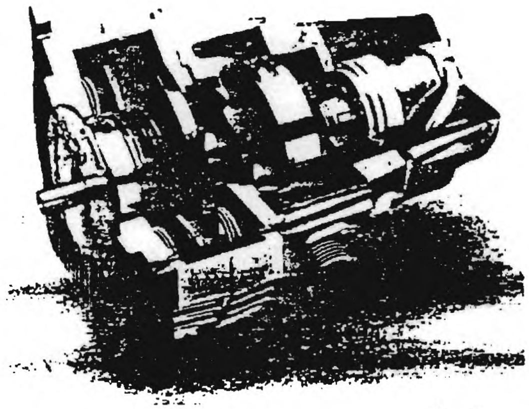
Consult Factory

Consult Factory

MAVILOR Servo Motor Systems

The Mavilor Motor Servo System incorporates the Mavilor motor and servo components that can be integrally mounted to the motor shaft. A variety of tachometers, brakes and encoders are available and these can be incorporated in a single motor housing to meet any custom requirement.

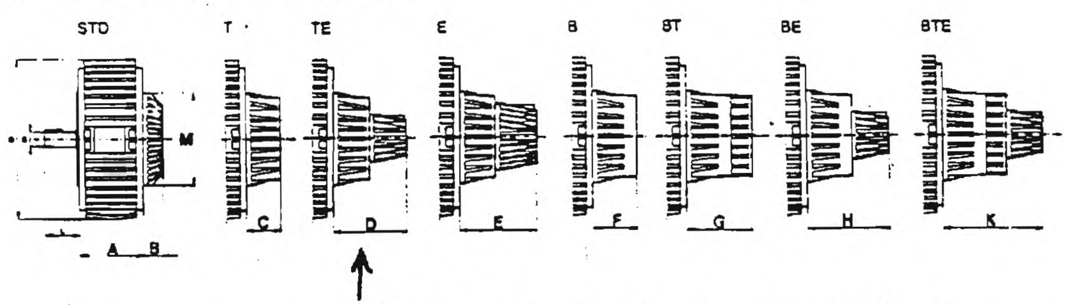
Motor options include: brush monitoring, waterproofing (IP65), hollow shaft, special shafts, and optional forced air cooling (available for higher performance).



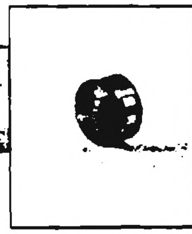
Motor System Configurations

STD = Standard Motor
T = Tachometer Option (Gradient: 10V/Krpm)
TE = Tachometer + Encoder Options
E = Encoder Option (Standard Resolution: 500 or 1000 ppr)
B = Brake Option (Standard Brake Voltage: 24Vdc)
BT = Brake + Tachometer Options
BE = Brake + Encoder Options
BTE = Brake + Tachometer + Encoder Options

NOTE: *Motors supplied with "integrated brake" have no appreciable increase in length due to this option.*

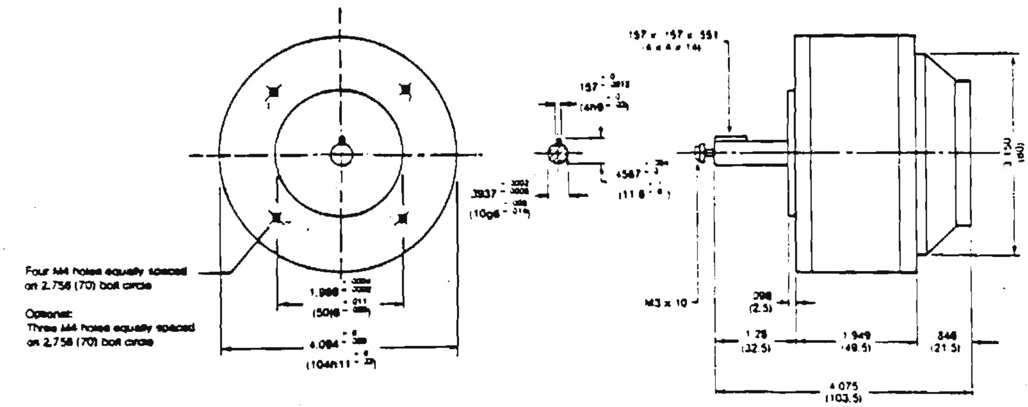


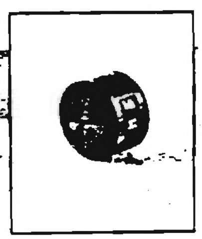
Dimension (inches) Mavilor Motor Model	S	L	O	A	B	C	D	E	F	G	H	K	M
Configuration (Options)						T	TE	E	B	BT	BE	BTE	
MO80/81/100 MT80	0.39	1.28	4.10	1.99	0.85	2.35	5.35	3.05	2.35	3.80	5.35	6.80	3.25
MO200/201 MT200	0.43	1.07	4.53	2.68	1.05	2.55	5.55	5.10	2.55	4.00	5.55	7.00	4.10
MO300/301 MT300	0.55	1.36	6.50	2.84	1.50	2.60	5.60	5.10	2.60	4.25	5.60	7.25	4.05
MO600/601.602 MT600	0.55	1.32	7.37	2.76	1.50	2.70	5.70	4.80	2.70	4.25	5.70	7.25	4.95
MO800	0.55	1.32	7.49	2.76	1.50	2.70	5.70	4.80	2.70	4.25	5.70	7.25	4.95
MO1000/1001/1002/1006 MT1000	0.95	2.15	8.43	3.59	1.40	2.85	5.85	5.00	3.00	4.60	6.00	7.60	5.95
MO2000 MT2000	0.95	2.15	10.63	4.39	1.55	2.65	5.65	4.90	3.00	4.55	6.00	7.55	6.90
MO3000/3001/3002	1.10	2.54	12.01	4.85	1.55	2.65	5.65	4.90	3.00	4.55	6.00	7.55	6.90
MO4500/4501 MT4500	1.10	2.54	12.01	4.85	1.55	2.65	5.65	4.90	3.20	4.80	6.20	7.80	6.90
MO7000/7001/7002	1.50	3.43	15.44	6.30	2.05	2.05	5.05	5.00	4.60	6.20	7.60	9.20	9.85
MO10000	1.65	4.57	16.90	6.78	2.05	2.05	5.05	5.00	4.60	6.20	7.60	9.20	9.85



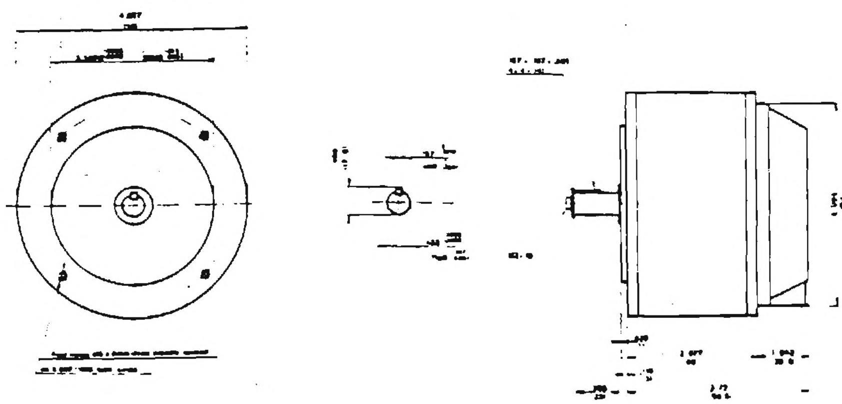
Motor Dimensions in inches (millimeters)

MO80
MO81
MO100 MT80

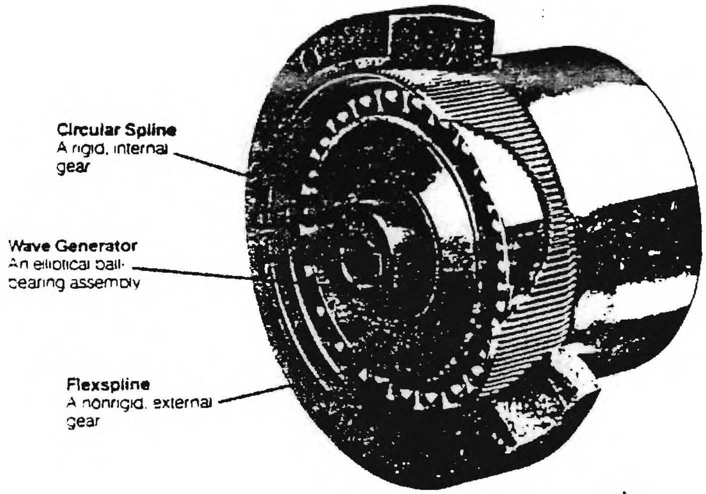




MO200
MO201



Harmonic Drive Gearing



CUP-TYPE GEARING COMPONENTS.

Because Harmonic Drive gearing consists of only three simple parts and requires relatively small space, it offers the design engineer extremely wide latitude including the freedom to integrate drives within other components of the equipment itself using relatively simple support structure.

Harmonic Drive's precision performance characteristics are ideal where accurate positioning or precise motion control is required.

Zero Backlash

Natural gear preload and almost pure radial tooth engagement allow standard Harmonic Drive gearing to operate with essentially zero backlash.

Efficiencies as High as 90%

Efficiencies measured on actual shaft-to-shaft losses rather than tooth losses, as in other gearing, are normally in the 90% range with standard Harmonic Drive gearing.

Simple Support Requirements

Since torque is transmitted by pure couple, Harmonic Drive gearing does not generate radial loads and, therefore, requires much simpler bearings and supporting structure than other forms of gearing.

High Single-Stage Ratios to 60:1 and up

With in-line input and output, single-stage ratios go as high as 320:1. By using compound drives, much higher ratios can also be achieved.

Torque Equal to Drive Twice as Large

Pound for pound, no other mechanical power transmission can compare with Harmonic Drive, and the extremely small size makes them easy to integrate into designs.

Excellent Positional Accuracy and Repeatability

The effect of tooth-to-tooth error is minimized with Harmonic Drive, since about 10% of the total teeth are always in engagement. Accuracy is in the arc minute range, and repeatability is in the arc second range.

Concentric Shafting

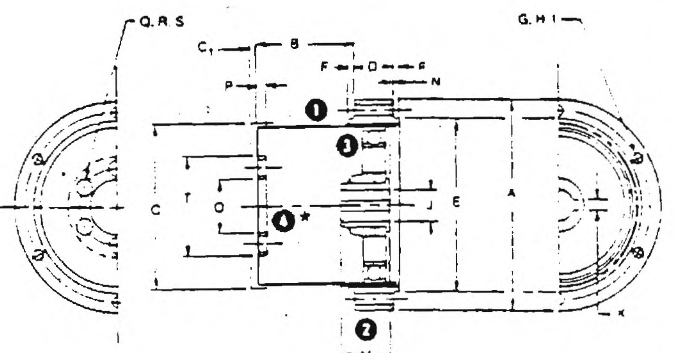
Ideal for differential designs.

Dimensions Cup-Type Model HDC

	10	1C	3C	5C	1M	2M	4M	8M	15M	30M
ENVELOPE										
A Circular Spline OD	1.48	2.00	2.62	3.29	4.25	5.25	6.62	8.62	10.62	13.38
B axial mounting control dim.	.71	.94	1.27	1.56	2.03	2.50	3.20	4.16	5.06	6.38
C flexing clearance diam.	1.03	1.47	2.06	2.56	3.33	4.11	5.16	6.66	8.19	10.23
C_1 axial flexing clearance	—	.08	.07	.08	.09	.11	.13	.16	.19	.50
D Circular Spline width	.28	.38	.50	.62	.81	1.00	1.09	1.44	1.88	2.25
MOUNTING										
E pilot diam.	1.078	1.500	2.141	2.672	3.500	4.282	5.344	6.954	8.563	10.688
F pilot width	.06	.09	.11	.12	.12	.14	.16	.19	.25	.25
G no. of holes	4	6	6	6	6	6	6	6	8	8
H hole size	.13	.10	.14	.19	.22	.28	.41	.47	.47	.53
I bolt circle diam.	1.28	1.75	2.38	2.94	3.81	4.69	5.88	7.62	9.50	11.50
INPUT										
J hub ID	.188	.250	.375	.500	.500	.625	.625	.875	1.125	1.375
K keyway	—	—	3/32 x 3/64	1/8 x 1/16	1/8 x 1/16	3/16 x 3/32	3/16 x 3/32	3/16 x 3/32	1/4 x 1/8	5/16 x 5/32
M length, coupling	.44	.62	.75	1.00	1.00	1.50	1.50	1.88	2.44	2.94
N mount face to hub	.108	.003	.029	.062	.099	.075	.047	.105	.088	.125
OUTPUT*										
O Flexspline pilot diam.	.313	.437	.625	.781	1.063	1.281	1.625	2.094	2.563	3.188
P mounting width	.2	.19	.12	.12	.19	.25	.25	.31	.38	1.00
Q no. of holes	—	6	6	6	6	5	5	6	6	6
R hole diam.	—	.12	.19	.22	.34	.41	.41	.53	.78	.91
S bolt circle diam.	—	.66	.94	1.19	1.53	1.88	2.31	3.06	3.75	4.62
T clamp ring OD	.56	.83	1.25	1.55	2.02	2.48	3.09	4.03	4.97	6.22
WEIGHT–LB										
Component set	.17	.3	.62	1.2	2.6	5.1	9.0	20.3	38.6	72.5

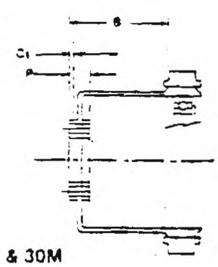
*Clamp ring is supplied as a loose item.
Sizes 1C & 30M is supplied with integral hub diaphragm

NOTE: Dimensions are for reference only. Required specification prints furnished on request. It is recommended that our engineering staff be given the opportunity to review application approaches since the full extent of design options is more than can be conveniently described in this brochure.

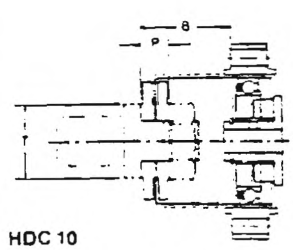


HDC 3C — 15M

1 FLEXSPLINE
2 CIRCULAR SPLINE
3 WAVE GENERATOR
4 CLAMP RING



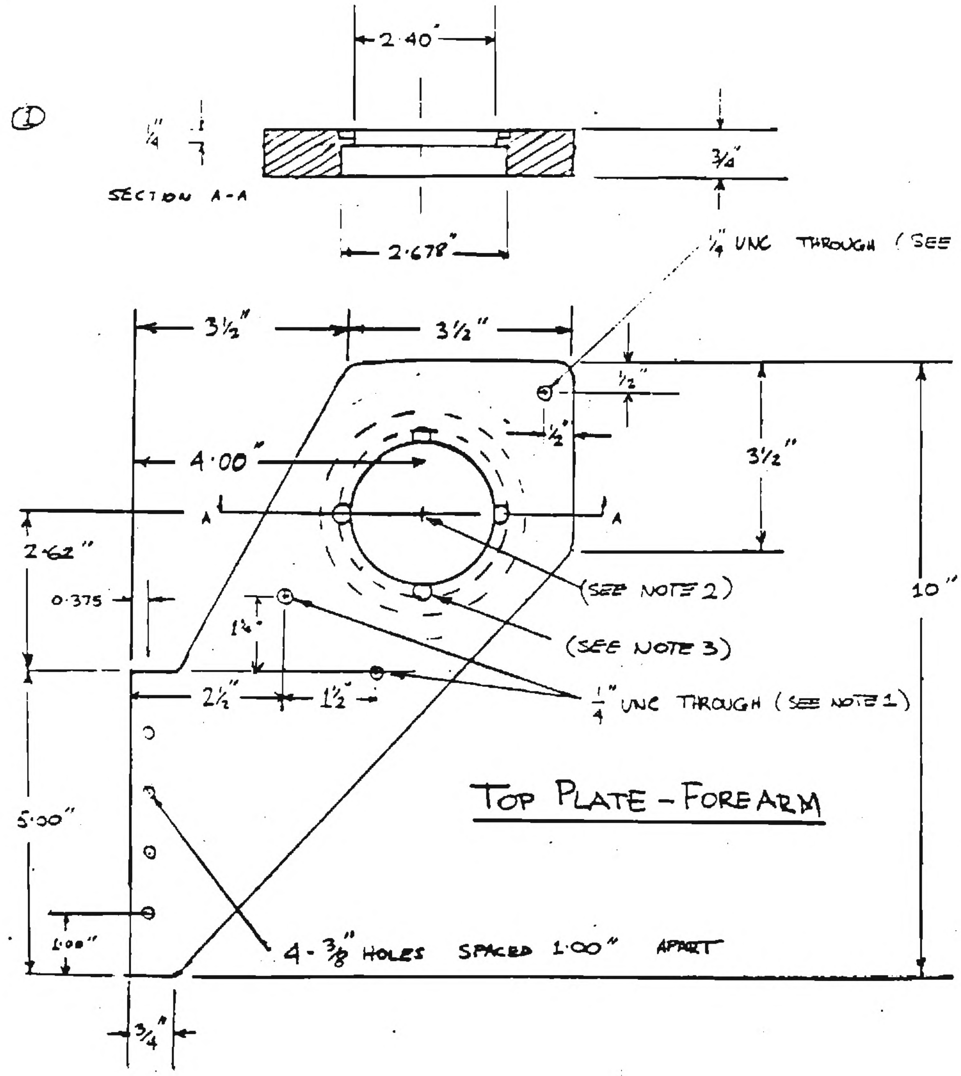
HDC 1C & 30M



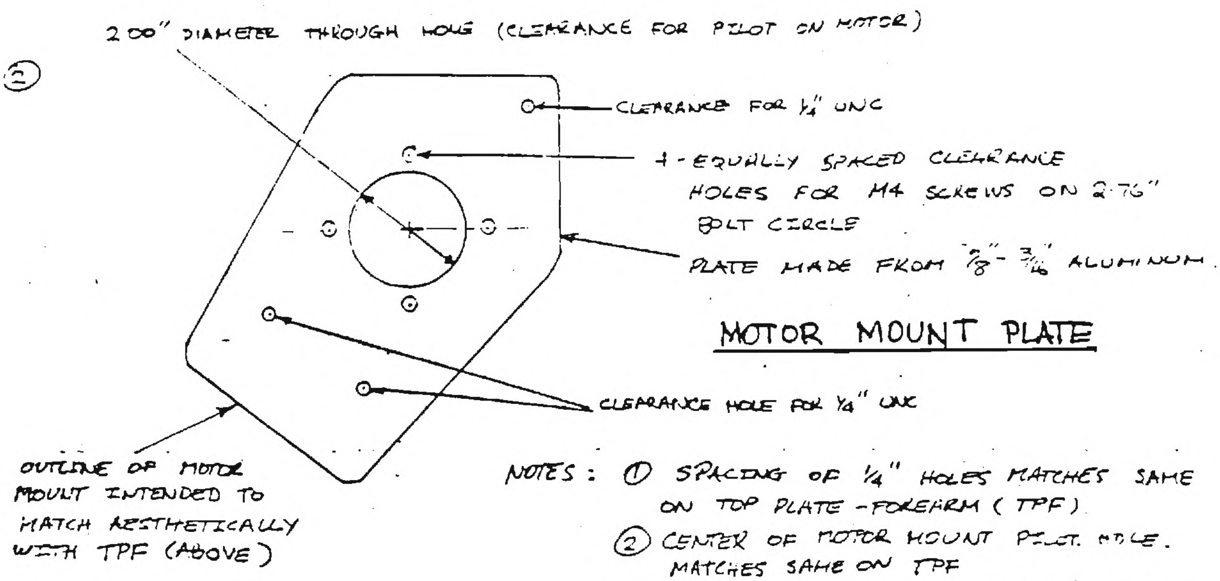
HDC 10

Rating Table (lb.-in.) HDC

HDC	Ratio***	3500 RPM Input HP	3500 RPM Output Speed	3500 RPM Output Torque	1750 RPM Input HP	1750 RPM Output Speed	1750 RPM Output Torque	1150 RPM Input HP	1150 RPM Output Speed	1150 RPM Output Torque	500 RPM Output Speed	500 RPM Output Torque	Max.** Output Torque
10	60	.02	58.3	21.4	.01	29.2	27	.01	19.2	30	8.3	30	30
	80	.02	43.8	22.2	.01	21.9	23	.01	14.4	32.2	6.3	40	40
1C	60	.06	58.3	68	.04	29.2	86	.03	19.2	95	8.3	110	119
	72	.06	48.6	68	.04	24.3	86	.03	16.0	95	6.9	110	119
	80	.06	43.8	68	.03	21.9	86	.02	14.4	95	6.3	110	140
	100	.05	35.0	68	.03	17.5	86	.01	11.5	95	5.0	110	180
3C	60	.22	58.3	240	.15	29.2	300	.10	19.2	300	8.3	300	300
	80	.20	43.8	240	.12	21.9	300	.08	14.4	300	6.3	300	300
	100	.16	35.0	240	.11	17.5	315	.07	11.5	350	5.0	450	410
	120	.14	29.2	240	.09	14.6	315	.07	9.6	350	4.2	430	480
	140	.12	25.0	240	.08	12.5	315	.06	8.2	350	3.6	430	590
	160	.11	21.9	240	.07	10.9	315	.05	7.2	350	3.1	430	660
5C	60	.38	58.3	410	.27	29.2	525	.19	19.2	570	8.3	570	570
	80	.34	43.8	410	.21	21.9	525	.15	14.4	570	6.3	570	570
	100	.28	35.0	410	.18	17.5	525	.14	11.5	600	5.0	710	770
	120	.24	29.2	410	.16	14.6	525	.12	9.5	600	4.2	800	990
	140	.21	25.0	410	.14	12.5	525	.10	8.2	600	3.6	800	1,130
	160	.19	21.9	410	.12	10.9	525	.09	7.2	600	3.1	800	1,240
	180	.18	19.4	410	.11	9.7	525	.08	6.4	600	2.8	800	1,360
	200	.16	17.5	410	.10	8.8	525	.06	5.8	600	2.5	800	1,440
1M	60	.77	58.3	835	.54	29.2	1,050	.38	19.2	1,125	8.3	1,125	1,125
	80	.70	43.8	835	.41	21.0	1,050	.29	14.4	1,125	6.3	1,125	1,125
	100	.57	35.0	835	.36	17.5	1,050	.27	11.5	1,200	5.0	1,530	1,530
	120	.50	29.2	835	.31	14.6	1,050	.23	9.6	1,200	4.2	1,600	1,890
	140	.44	25.0	835	.27	12.5	1,050	.21	8.2	1,200	3.6	1,600	2,200
	160	.39	21.9	835	.24	10.9	1,050	.18	7.2	1,200	3.1	1,600	2,470
	180	.36	19.4	835	.22	9.7	1,050	.17	6.4	1,200	2.8	1,600	2,690
	200	.33	17.5	835	.21	8.8	1,050	.16	5.8	1,200	2.5	1,600	2,890
2M	60	1.62	58.3	1,750	.90	29.2	1,750	.59	19.2	1,750	8.3	1,750	1,750
	80	1.38	43.8	1,750	1.30	21.0	1,750	.45	14.4	1,750	6.3	1,750	1,750
	100	1.23	35.0	1,800	.75	17.5	2,200	.52	11.5	2,430	5.0	2,430	2,430
	120	1.07	29.2	1,800	.65	14.6	2,200	.49	9.6	2,500	4.2	2,900	2,900
	140	.94	25.0	1,800	.57	12.5	2,200	.43	8.2	2,500	3.6	3,400	3,500
	160	.84	21.9	1,800	.51	10.9	2,200	.38	7.2	2,500	3.1	3,400	3,940
	180	.77	19.4	1,800	.47	9.7	2,200	.35	6.4	2,500	2.8	3,400	4,280
	200	.71	17.5	1,800	.44	8.8	2,200	.33	5.8	2,500	2.5	3,400	4,630
4M	60	3.03	58.3	3,280	1.69	29.2	3,280	1.11	19.2	3,280	8.3	3,280	3,280
	80	2.59	43.8	3,280	1.34	21.9	3,280	.85	14.4	3,280	6.3	3,280	3,280
	100	2.28	35.0	3,300	1.29	17.5	4,100	.93	11.5	4,370	5.0	4,370	4,370
	120	1.96	29.2	3,300	1.21	14.6	4,100	.92	9.6	4,700	4.2	5,500	5,500
	140	1.72	25.0	3,300	1.07	12.5	4,100	.80	8.2	4,700	3.6	6,300	6,460
	160	1.55	21.9	3,300	.96	10.9	4,100	.72	7.2	4,700	3.1	6,300	7,250
	180	1.41	19.4	3,300	.88	9.7	4,100	.66	6.4	4,700	2.8	6,300	7,950
	200	1.31	17.5	3,300	.82	8.8	4,100	.62	5.8	4,700	2.5	6,300	8,530
8M	60	5.55	58.3	6,000	3.42	29.2	6,650	2.25	19.2	6,650	8.3	6,650	6,650
	80	4.74	43.8	6,000	2.63	21.9	6,650	1.73	14.4	6,650	6.3	6,650	6,650
	100	4.11	35.0	6,000*	2.54	17.5	7,600	1.96	11.5	8,700	5.0	9,280	9,280
	120	3.56	29.2	6,000*	2.25	14.6	7,600	1.70	9.6	8,700	4.2	11,200	[illegible]
	140	3.13	25.0	6,000*	1.98	12.5	7,600	1.50	8.2	8,700	3.6	11,700	[illegible]
	160	2.82	21.9	6,000*	1.78	10.9	7,600	1.34	7.2	8,700	3.1	11,700	14,800
	180	2.57	19.4	6,000*	1.62	9.7	7,600	1.23	6.4	8,700	2.8	11,700	16,200
	200	2.38	17.5	6,000*	1.52	8.8	7,600	1.14	5.8	8,700	2.5	11,700	17,600
15M	60				5.96	29.2	11,570	3.92	19.2	11,570	8.3	11,570	11,570
	80				4.57	21.9	11,570	3.00	14.4	11,570	6.3	11,570	11,570
	100				5.14	17.5	15,000	3.41	11.5	16,000	5.0	16,000	16,000
	120				4.45	14.6	15,000	3.42	9.6	17,500	4.2	20,000	20,000
	140				3.91	12.5	15,000	2.99	8.2	17,500	3.6	23,000	23,600
	160				3.51	10.9	15,000	2.70	7.2	17,500	3.1	23,000	27,000
	180				3.21	9.7	15,000	2.47	6.4	17,500	2.8	23,000	29,500
	200				2.99	8.8	15,000	2.30	5.8	17,500	2.5	23,000	31,700
30M	60				14.4	29.2	28,000	10.8	19.2	32,000	8.3	36,200	36,200
	80				11.05	21.9	28,000	8.31	14.4	32,000	6.3	36,200	36,200
	100				9.60	17.5	28,000	7.21	11.5	32,000	5.0	43,000	48,400
	120				8.32	14.6	28,000	6.25	9.6	32,000	4.2	43,000	59,500
	140				7.31	12.5	28,000	5.48	8.2	32,000	3.6	43,000	68,700
	160				6.54	10.9	28,000	4.94	7.2	32,000	3.1	43,000	77,700
	180				5.98	9.7	28,000	4.51	6.4	32,000	2.8	43,000	84,200
	200				5.58	8.8	28,000	4.21	5.8	32,000	2.5	43,000	89,200



TOP PLATE - FOREARM

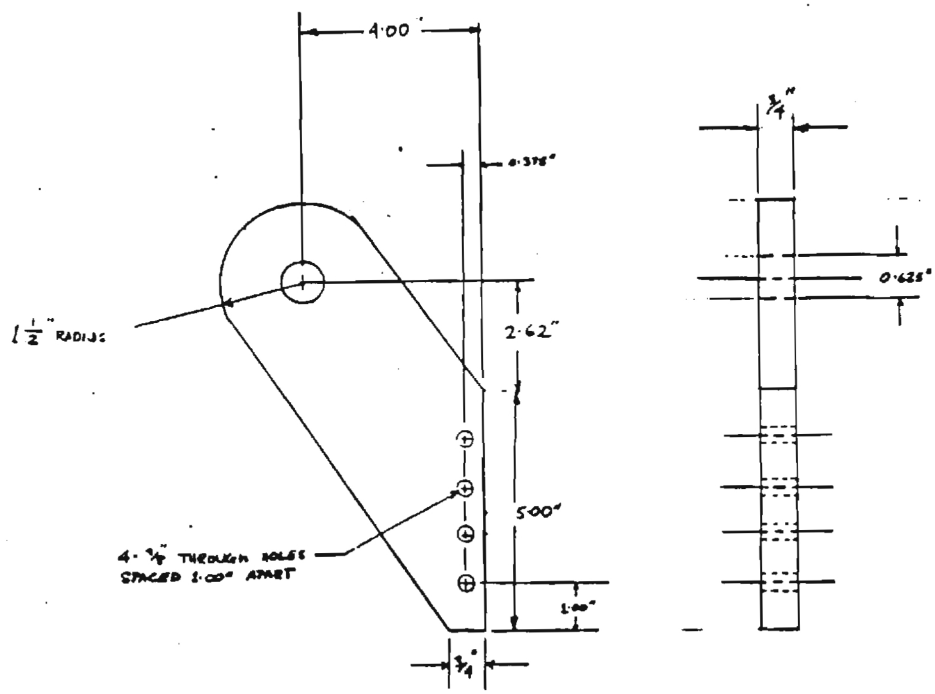


MOTOR MOUNT PLATE

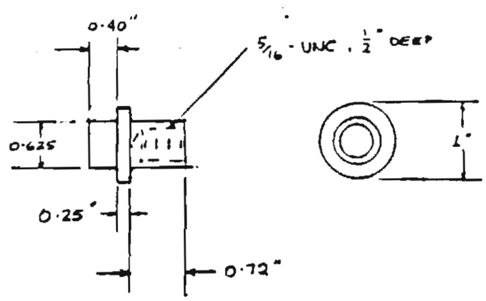
NOTES:
1. SPACING OF ¼" HOLES MATCHES SAME ON TOP PLATE - FOREARM (TPF)
2. CENTER OF MOTOR MOUNT PILOT HOLE MATCHES SAME ON TPF
3. TPF COUNTER-SUNK FOR M4 SCREW HEADS

(1) BOTTOM PLATE - UPPER ARM
(2) LOWER BEARING PLUG

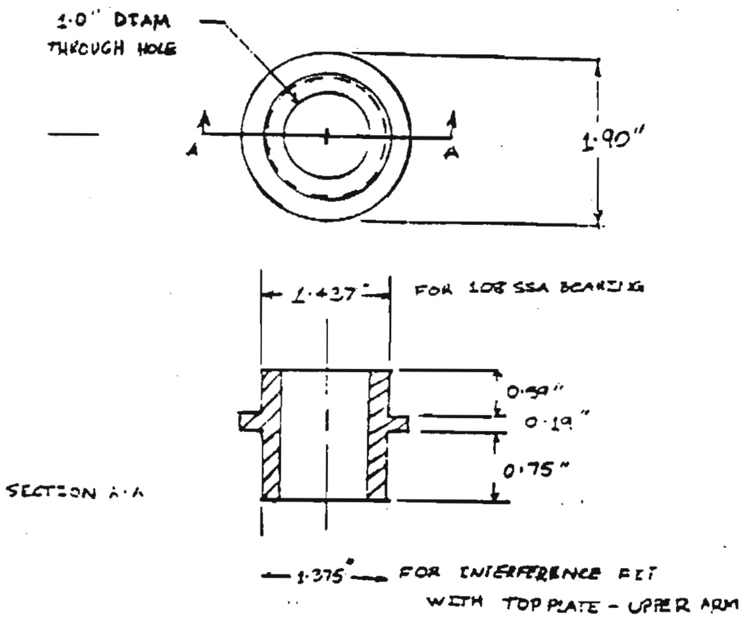
(1)



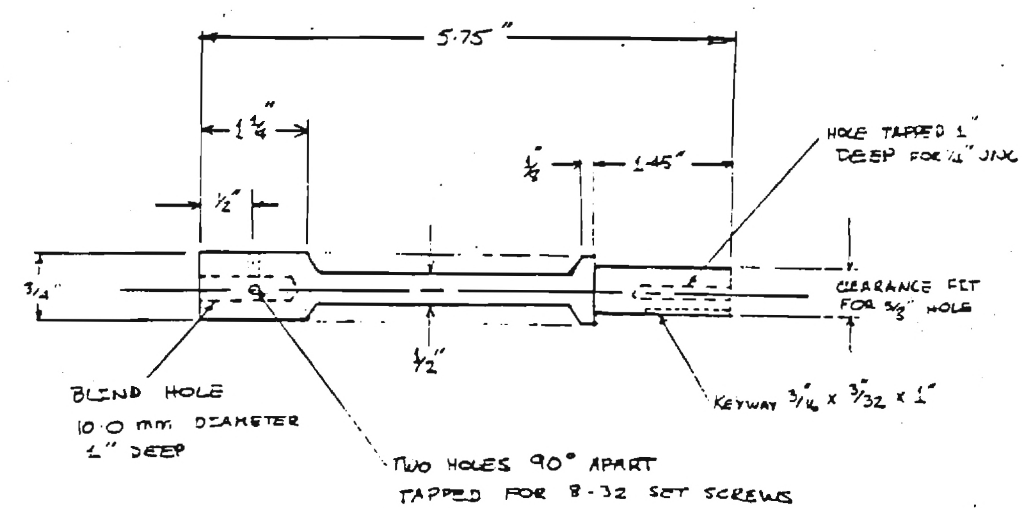
(2)



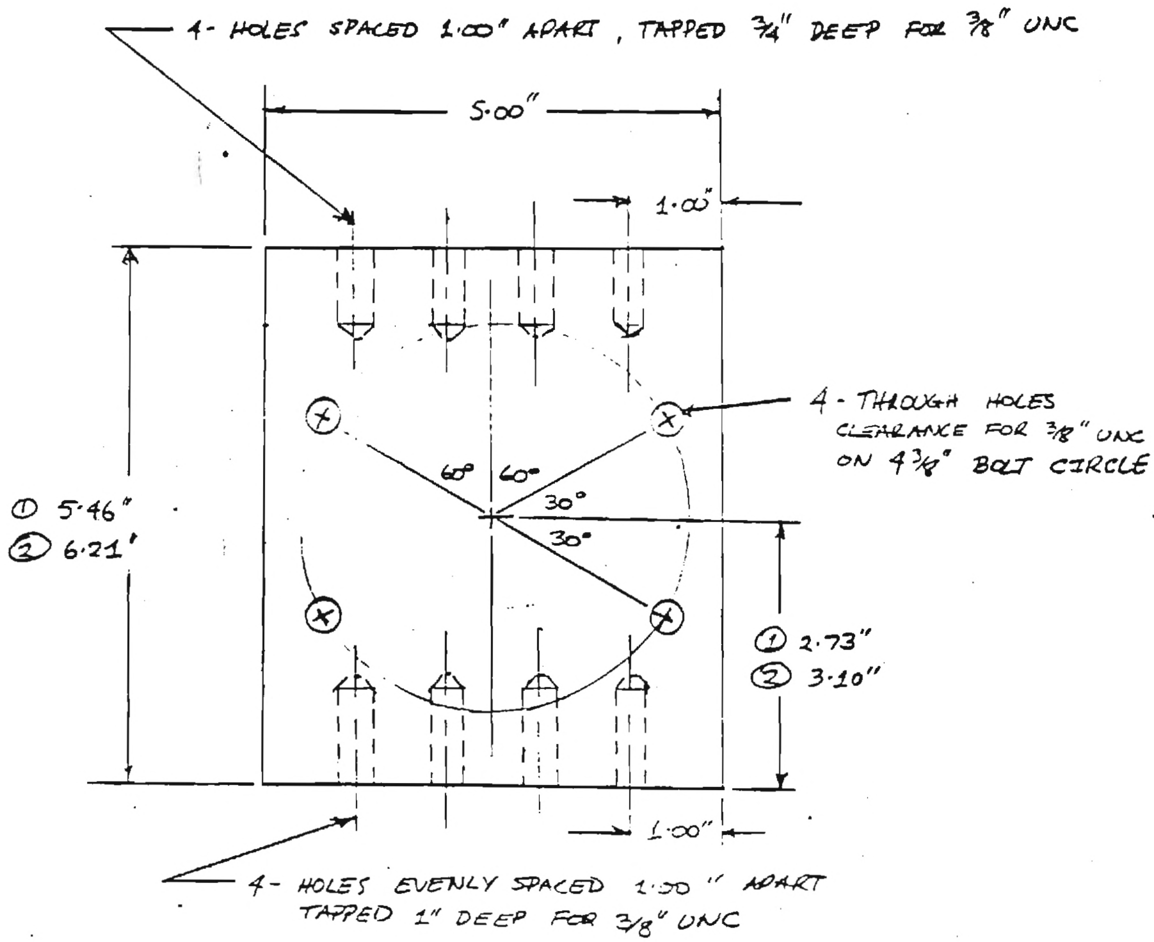
A. UPPER BEARING HOLDER
B. MOTOR - W/GENER. COUPLING



NOTE: MILD STEEL



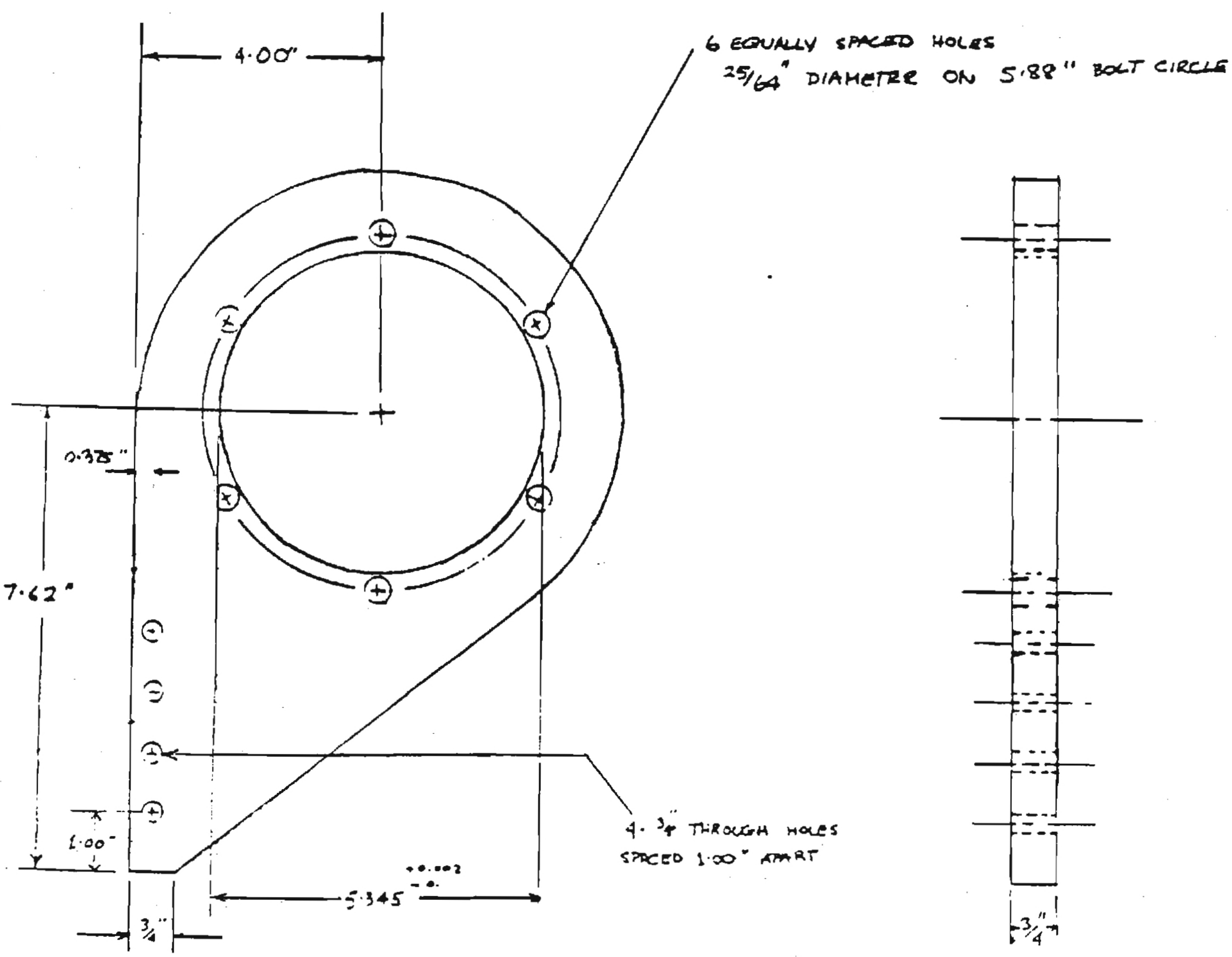
NOTE: MILD STEEL



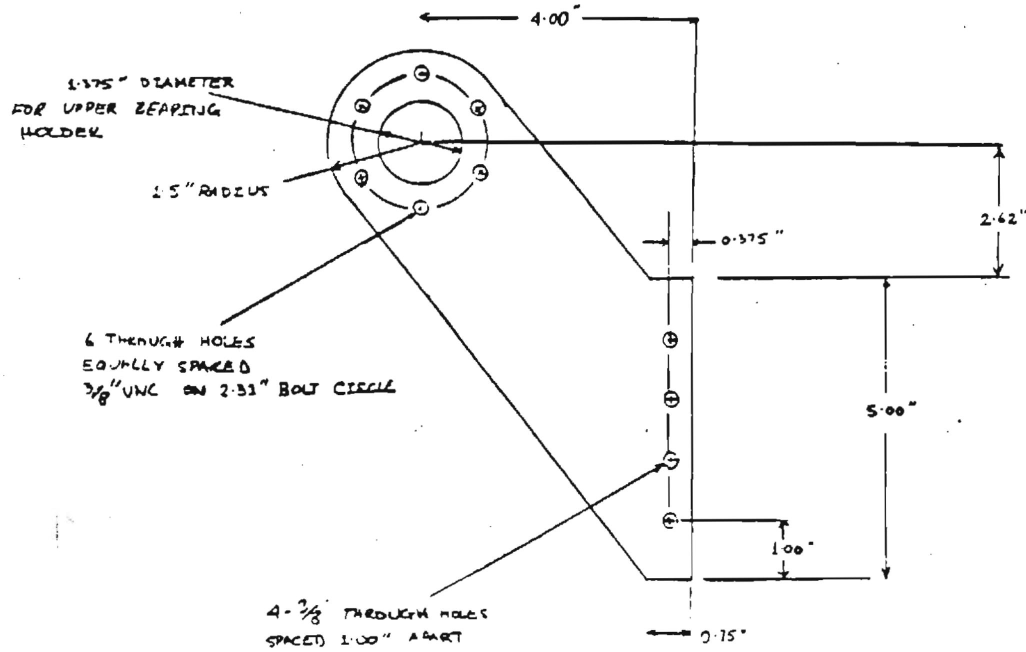
NOTES: ① TWO PLATES ARE NEEDED, DIFFERING ONLY IN THE HEIGHT DIMENSIONS SHOWN, AND IN THE PRESENCE OF A COUNTERBORE ON ONE OF THE PLATES

② BOTH PLATES MADE FROM 3/4" ALUMINUM

BOTTOM PLATE - FOREARM

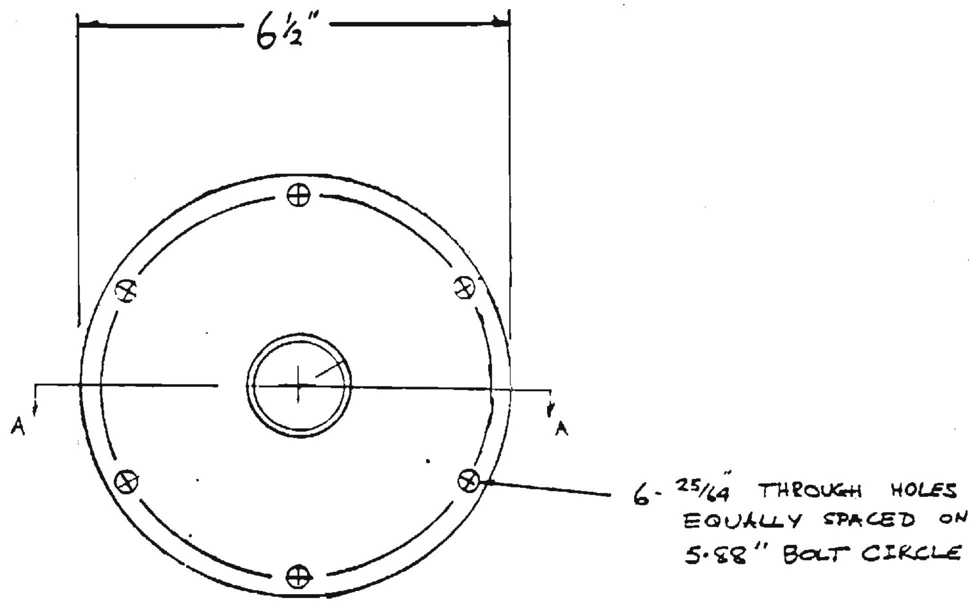


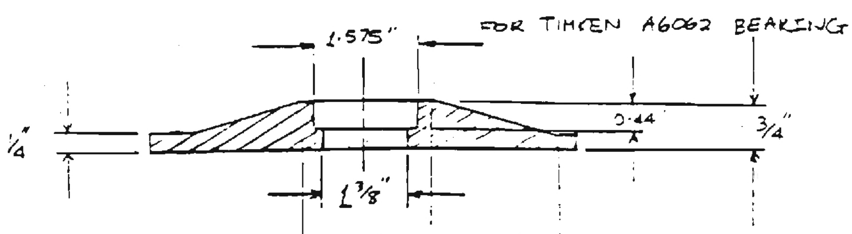
TOP PLATE - UPPER ARM



NOTE: PLATE CUT FROM 3/4" ALUMINUM

BEARING SUPPORT PLATE - FOREARM





Appendix D

TUBULAR LINKS AND PASSIVE DAMPING MATERIAL

LINKS

LENGTH BETWEEN FLANGE MOUNTING FACES:
UPPER ARM - 16 in.
FOREARM - 44 in.

MATERIAL: ALUMINUM, 6061-T6

SIZE: OUTSIDE DIAMETER - 3.500 in.
WALL THICKNESS - 0.083 in.

FLANGES: OUTSIDE DIAMETER - 5.25 in.
BOLT CIRCLE - 4.375 in.

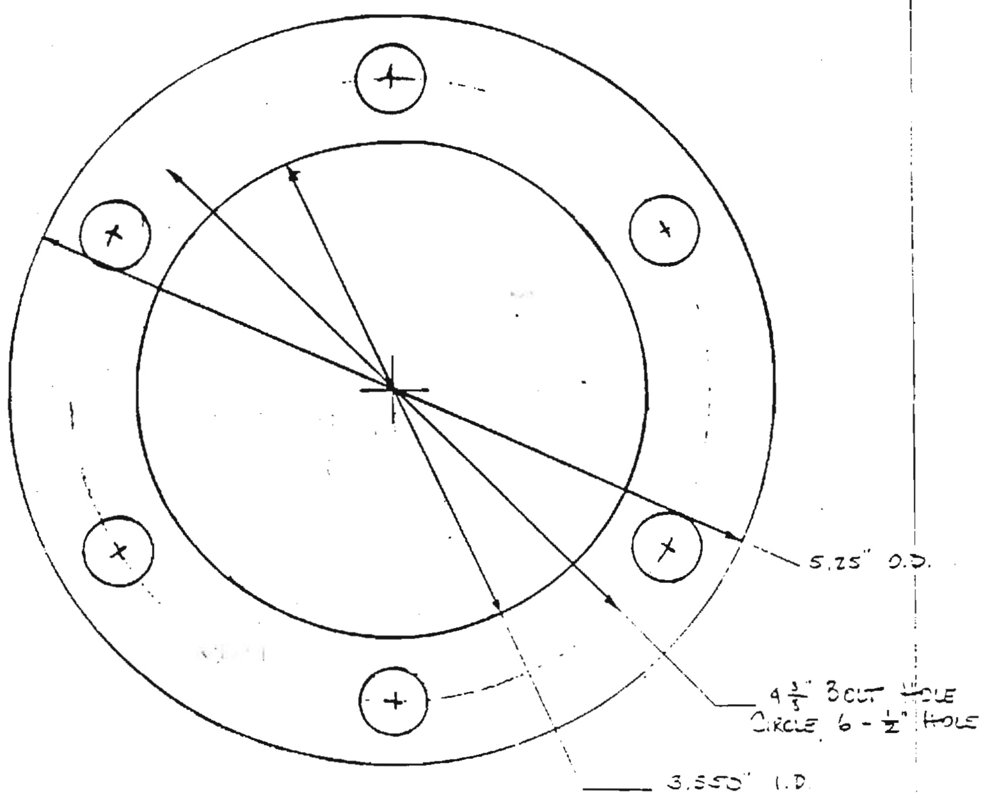
NOTE: LINKS TREATED WITH PASSIVE DAMPING MATERIAL

6/26/86

Erin Leeson
774-6035
352-1611

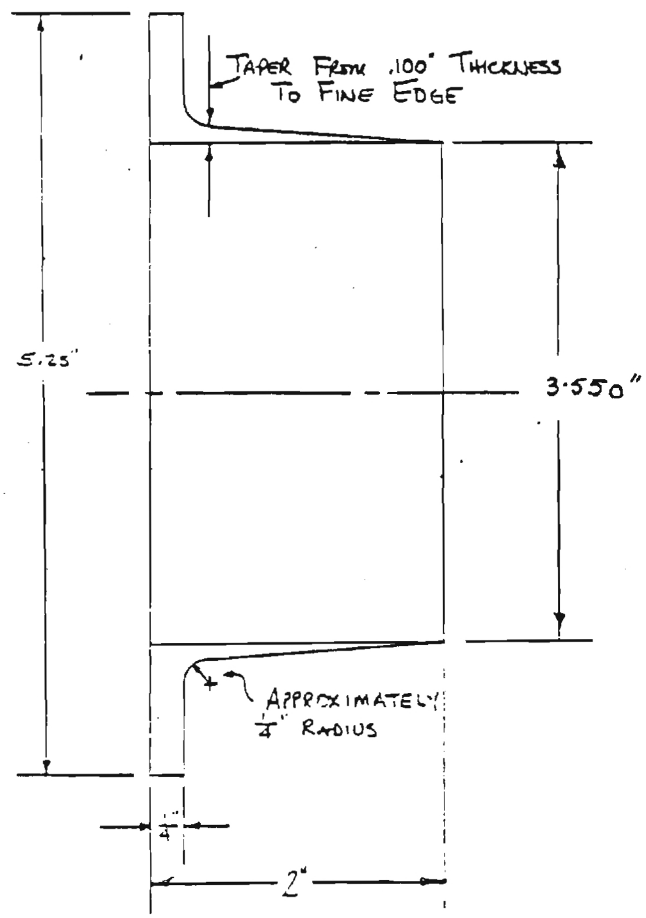
FLANGE END VIEW

revised 7/26/86



IF NECESSARY, MILL 3/4" FLAT ON TOP OF EACH HOLE FOR BOLT HEAD TO HAVE FLAT MATING SURFACE

FLANGE CROSS-SECTION



Scotch-Weld® BRAND 3M

Technical Data

Dated: June 1, 1984
Supersedes previous product data for Scotch-Weld Brand products 2216 B/A Gray and 2216 B/A Clear

Epoxy Adhesives
2216 B/A Gray
2216 B/A Translucent

Description:

- Flexible, two part, room temperature curing structural adhesives with high shear and peel strengths.
- Excellent for bonding rubber, metal, wood, most plastics and masonry products.

Typical Physical Properties:

Product	Color	Base	Net Wt. Lbs./Gal.	Viscosity (cps) (Approx.) Brookfield RVF #7sp. @ 20 rpm	Mix Ratio (By Weight)	Mix Ratio (By Volume)	Work Life (Approx. Time for 100 Gram Qty. @ 75°F)
2216 B/A Gray Base	White	Modified Epoxy	11.1 ± .2	100,000	5 parts	2 parts	90 minutes
Accelerator	Gray	Modified Amine	10.5 ± .2	52,000	7 parts	3 parts	
2216 B/A Trans. Base	Transparent	Modified Epoxy	9.6	14,000	1 part	1 part	90 minutes
Accelerator	Amber	Modified Amine	8.2	7,000	1 part	1 part	

Application and Equipment Suggestions:

These products may be applied with spatula, trowel or flow equipment. Suitable two-part metering and mixing equipment is available from several companies. Contact your 3M representative for assistance in selecting application equipment to suit your specific needs.

Directions For Use:

1. Surfaces must be clean, dry and free from paint, rust, oil, grease or wax. Surfaces can be cleaned by sanding with 3M Brand Coated Abrasives (240 grit) followed by solvent wiping with 3M Brand Solvent #3 or #4* Scotch-Weld Brand Degreasing Primer 3911 should be used in applications that demand ultimate performance. *See note under storage and handling.
2. These products consist of two parts, base and accelerator. Mix thoroughly by weight.

2216 B/A Gray	2216 B/A Translucent
5 Parts Base	1 Part Base
7 Parts Accelerator	1 Part Accelerator
(Color should be a uniform gray.)	(Color should be uniform.)

(Replace caps on proper tubes.) Use within 90 minutes.

3. For maximum bond strength apply product evenly to both surfaces to be joined.
4. **Join the adhesive coated surfaces and allow to cure at 60°F or above until completely firm. Overnight curing at 75°F is usually sufficient. In addition to the standard room temperature cure, the following times and temperatures will give a minimum of 2000 psi tensile shear strength at 75°F (See chart below.)**
5. Keep parts from moving during cure. Contact pressure is necessary.

	Time	
Cure Temperature	**2216 Gray**	**2216 Translucent**
40°F	7 days	–
150°F	120 minutes	240 minutes
200°F	30 minutes	60 minutes

Performance Characteristics:

1. Minimum Overlap Shear Strength
(PSI) ASTM D-1002-64

	Aluminum FPL Etch	
Test Temp.	**2216 B/A Gray**	**2216 B/A Trans.**
−67°F	2000	3000
75°F	2500	1200*
180°F	400	200

2. Minimum T-Peel Strength
(PIW) ASTM D-1876-61T

	Aluminum PFL Etch	
Test Temp.	**2216 B/A Gray**	**2216 B/A Trans.**
75°F	25	25

NOTE: Data developed using 7 day cure @ 75°F, 2 psi. *2216 B/A Translucent will reach 2500 psi in 30 days.

3. Etched Aluminum Overlap Shear Strength After Environmental Aging

		Test Results (75°F)	
Environment	**Time**	**2216 B/A Gray**	**2216 B/A Translucent**
100% Relative Humidity @ 120°F	14 days	2950 psi	
	30 days	1985 psi	1390 psi
	90 days	1505 psi	
Salt Spray @ 95°F	14 days	2300 psi	
	30 days	500 psi	1260 psi
	60 days	300 psi	
Tap Water @ 75°F	14 days	3120 psi	
	30 days	2942 psi	1950 psi
	90 days	2075 psi	
Air @ 160°F	35 days	4650 psi	
Air @ 300°F	8 days	4000 psi	3500 psi
Anti-icing Fluid @ 75°F	7 days	3300 psi	2500 psi
Hydraulic Oil @ 75°F	30 days	2500 psi	2500 psi
JP-4 Fuel	30 days	2500 psi	2500 psi
Hydrocarbon Fluid	7 days	3300 psi	3000 psi

4. Overlap Shear Strength Comparison on Aluminum Substrates Evaluating Various Cleaning Methods

Aluminum Substrate	Cleaning	Shear Strength (75°F) 2216 B/A Gray
2024 T3 Clad	FPL Acid Etch	3400 psi
	SCOTCH-BRITE* Abrade – Solvent Wipe	2350 psi
	Sanded (240 grit) – Solvent Wipe	2340 psi

5. Thermal Conductivity

2216 B/A Gray	2216 B/A Translucent
0.228 BTU/HR/SQ. FT./°F./FT.	0.114 BTU/HR/SQ. FT./°F./FT.

6. Coefficient of Thermal Expansion

2216 B/A Gray	2216 B/A Translucent
102×10^{-6} in./in./°C. between 0-40°C.	81×10^{-6} in./in./°C between -50-0°C
134×10^{-6} in./in./°C. between 40-80°C.	207×10^{-6} in./in./°C. between 60-150°C.

7. Electrical Properties

2216 B/A Gray	
Arc Resistance	130 seconds
Dielectric Strength	408 volts/mil
Dielectric Constant @ 73°F	5.51 – Measured @ 1.00 KC
Dielectric Constant @ 140°F	14.17 – Measured @ 1.00 KC
Dissipation Factor @ 73°F	0.112 – Measured @ 1.00 KC
Dissipation Factor @ 140°F	0.422 Measured @ 1.00 KC
Surface Resistivity @ 73°F	5.5×10^{14} ohms – @ 500 volts DC
Volume Resistivity @ 73°F	1.9×10^{12} ohms-cm – @ 500 volts DC

2216 B/A Translucent
Dielectric Strength 630 volts/mil
Volume Resistivity @ 73°F 3.0×10^{12} ohms-cm @ 500 volts DC

Note: All the above data developed using 7 day cure @ 75°F, 2 psi.

Storage and Handling:

Store products at 60-80°F. for maximum storage life. Higher temperatures reduce normal storage life. Lower temperatures cause increased viscosity of a temporary nature. Rotate stock on a "first in-first out" basis. Upon request, your 3M Adhesives, Coatings and Sealers Sales Representative will be pleased to advise you of the anticipated shelf life of either product under the storage conditions in your plant.

Cleanup can be accomplished with Scotch Grip Brand Solvent No. 3 or No. 4. When using solvents for cleanup, it is essential that proper precautionary measures for handling such materials be observed.

Shipping Information:

National Motor Freight Classification: 2216-B Adhesives, NOI 2216-A Chemicals, NOI

The following information is provided to help you determine the proper packaging, labeling and marking in accordance with hazardous materials regulations.

D.O.T. Proper Shipping Name: Not Regulated

D.O.T. Hazard Classification: Not Regulated

Technical Name of Hazardous Ingredient: Not Applicable

Flash Point: None

Precautionary Information:

WARNING: These products consist of two components. The precautions for each part should be observed when separate or mixed.

Part A: DANGER. Extremely irritating to eyes. May cause permanent eye damage. May be irritating to skin. May cause a sensitization reaction in certain **individuals.** Contains amine.

Precautions: Prevent eye and skin contact.

Part B: CAUTION. May be irritating to skin. Contains epoxy resin.

Precautions: Prevent eye and skin contact.

Mixed A and B: Use only in well ventilated areas. Avoid inhalation or eye contact with dust from grinding operations on the cured material. Curing ovens must be vented to the outdoors. Wash contamined clothing before reuse. **Keep out of reach of children.**

Suggested First Aid: Eye Contact: Immediately flush eyes with plenty of water while holding the eyelids open and call a physician. Flushing eyes with water may not have the capability of preventing minor injury. **Skin contact:** Wash with soap and water.

Important Notice to Purchaser:

All statements, technical information and recommendations contained herein are based on tests we believe to be reliable, but the accuracy or completeness thereof is not guaranteed, and the following is made in lieu of all warranties, express or implied.

Seller's and manufacturer's only obligation shall be to replace such quantity of the product proved to be defective. Neither seller nor manufacturer shall be liable for any injury, loss or damage, direct or consequential, arising out of the use of or the inability to use the product. Before using, user shall determine the suitability of the product for his intended use, and user assumes all risk and liability whatsoever in connection therewith.

No statement or recommendation not contained herein shall have any force or effect unless in an agreement signed by officers of seller and manufacturer.

MEASUREMENTS GROUP, INC.; STRAIN GAGE SELECTION.

Table 1 Gage Coding System

Self-Temperature-Compensation — Active Gage Length in Mils

Foil Alloy — Grid and Tab Geometry

Carrier Matrix (Backing) — Resistance in Ohms

E A - 0 6 - 2 5 0 B G - 1 2 0 OPTION LE

E: Open-faced general purpose, polyimide backing, many options available.

M: Special epoxy backing for high accuracy transducers. Not for general purpose use.

W: Fully encapsulated gage, glass fiber reinforced epoxy phenolic resin. High endurance leadwires.

S: Identical to the "W" matrix, but with solder dot connections instead of leadwires.

A: Constantan alloy in self-temperature-compensated form.

P: Annealed Constantan. Used for high-elongation or post-yield gages.

D: Isoelastic alloy. High gage factor and high fatigue life.

K: Modified Karma alloy used for high-performance self-temperature-compensated gages.

The S-T-C number is the approximate thermal expansion coefficient in PPM/°F of the structural material on which the gage is to be used. The following standard compensations are available:

'A' Alloy: 03, 05, 06, 09, 13, 15

'P' Alloy: 08 only

'K' Alloy: 03, 05, 06, 09, 13, 15

'D' Alloy: Not available in self-temperature-compensated form.

OPTIONAL FEATURES

Most of these options apply to the EA or ED series gages as indicated in the Gage Listings Section.

W: Integral printed circuit terminal with polyimide encapsulation.

E: Polyimide encapsulation, leaving a portion of the solder tab exposed.

S: Solder dots on tabs.

LE: Leads plus polyimide encapsulation.

Gage Series	DESCRIPTION AND PRIMARY APPLICATION	TEMPERATURE RANGE	STRAIN RANGE	FATIGUE LIFE	
				Strain Level in Microstrain	Number of Cycles
EA	Constantan foil in combination with a tough, flexible, polyimide backing. Wide range of options available. Primarily intended for general-purpose static and dynamic stress analysis. Not recommended for highest-accuracy transducers.	Normal: −100° to +350° F (−75° to +175° C) Special or Short-Term: −320° to +400° F (−195° to +205° C)	±3% for gage lengths under 1/8 in (3.2 mm), ±5% for 1/8 in and over.	±1800 ±1500 ±1200	10^5 10^6 10^8
CEA	Universal general-purpose strain gage. Constantan grid completely encapsulated in polyimide, with large, integral, copper-coated terminals. Primarily used for general-purpose static and dynamic stress analysis.	−100° to +400° F (−75° to +205° C) Stacked rosettes limited to +125° F (+50° C)	±3% for gage lengths under 1/8 in (3.2 mm) ±5% for 1/8 in and over.	±1500 ±1500 *Fatigue life improved using low-modulus solder.	10^5 10^6 *
MA	Open-faced constantan gage on a thin special epoxy cast-film backing. Recommended for highest-accuracy transducers. Somewhat brittle nature of backing too delicate for general-purpose use. Only Option S is available.	Precision Static Transducer Service: −50° to +200° F (−45° to +95° C) Dynamic: −320° to +350° F (−195° to +175° C)	±2%	±1900 ±1700 ±1500	10^5 10^6 10^7
ED	Isoelastic foil in combination with tough, flexible polyimide film. High gage factor and extended fatigue life excellent for dynamic measurements. Not normally used in static measurements because of very high apparent-strain characteristic.	Dynamic: −320° to +400° F (−195° to +205° C)	±2% Nonlinear at strain levels over ±.5%	±2500 ±2200	10^6 10^7

ANALOG DEVICES 2B31L CONDITIONER

SPECIFICATIONS (typical @ +25°C and V_S = ±15V unless otherwise noted)

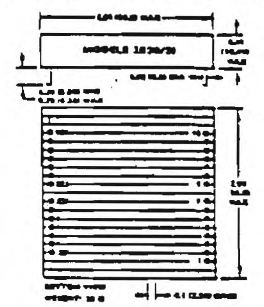
MODEL	2B30J 2B31J	2B30K 2B31K	2B30L 2B31L
GAIN*			
Gain Range	1 to 2000V/V	•	•
Gain Equation	G = [1 + 94kΩ/R_G] [20kΩ/(R_F + 16.2kΩ)]	•	•
Gain Equation Accuracy	±2%	•	•
Fine Gain (Span) Adjust. Range	±20%	•	•
Gain Temperature Coefficient	±25ppm/°C max (±10ppm/°C typ)	•	•
Gain Nonlinearity	±0.01% max	±0.005% max	±0.0025% max
OFFSET VOLTAGES[1]			
Total Offset Voltage, Referred to Input			
Initial, @ +25°C	Adjustable to Zero (±0.5mV typ)	•	•
Warm-Up Drift, 10 Min., G = 1000	Within ±5μV (RTI) of Final Value	•	•
vs. Temperature			
G = 1V/V	±150μV/°C max	±75μV/°C max	±50μV/°C max
G = 1000V/V	±3μV/°C max	±1μV/°C max	±0.5μV/°C max
At Other Gains	±(3 ± 150/G)μV/°C max	±(1 ± 75/G)μV/°C max	±(0.5 ± 50/G)μV/°C max
vs. Supply, G = 1000V/V[4]	±2.5μV/V	•	•
vs. Time, G = 1000V/V	±5μV/month	•	•
Output Offset Adjust. Range	±10V	•	•
INPUT BIAS CURRENT			
Initial @ +25°C	±200pA max (100pA typ)	•	•
vs. Temperature (0 to +70°C)	±0.6nA/°C	•	•
INPUT DIFFERENCE CURRENT			
Initial @ +25°C	±5nA	•	•
vs. Temperature (0 to +70°C)	±90pA/°C	•	•
INPUT IMPEDANCE			
Differential	100MΩ‖47pF	•	•
Common Mode	100MΩ‖47pF	•	•
INPUT VOLTAGE RANGE			
Linear Differential Input	±10V	•	•
Maximum Differential or CMV Input Without Damage	±30V rms	•	•
Common Mode Voltage	±10V	•	•
CMR, 1kΩ Source Imbalance			
G = 1V/V, dc to 60Hz[2]	90dB	•	•
G = 100V/V to 2000V/V, 60Hz[2]	140dB min	•	•
dc[3]	90dB min (112 typ)	•	•
INPUT NOISE			
Voltage, G = 1000V/V			
0.01Hz to 2Hz	1μV p-p max	•	•
10Hz to 100Hz[2]	2μV p-p	•	•
Current, G = 1000			
0.01Hz to 2Hz	70pA p-p	•	•
10Hz to 100Hz[2]	10pA rms	•	•
RATED OUTPUT[3]			
Voltage, 2kΩ Load[3]	±10V min	•	•
Current	±5mA min	•	•
Impedance, dc to 2Hz, G = 100V/V	0.1Ω	•	•
Load Capacitance	0.01μF max	•	•
DYNAMIC RESPONSE (Unfiltered)[3]			
Small Signal Bandwidth			
±3dB Gain Accuracy, G = 100V/V	10kHz	•	•
G = 1000V/V	1kHz	•	•
Slew Rate	1V/μs	•	•
Full Power	15kHz	•	•
Settling Time, G = 100, ±10V Output Step to ±0.1%	10μs	•	•
LOW PASS FILTER (Bessel)			
Number of Poles	3	•	•
Gain (Pass Band)	+1	•	•
Cutoff Frequency (−3dB Point)	2Hz	•	•
Roll-Off	60dB/decade	•	•
Offset (at 25°C)	±5mV	•	•
Settling Time, G = 100V/V, ±10V Output Step to ±0.1%	600ms	•	•
BRIDGE EXCITATION (See Table 1)			
POWER SUPPLY[4]			
Voltage, Rated Performance	±15V dc	•	•
Voltage, Operating	±(12 to 18)V dc	•	•
Current, Quiescent[7]	±15mA	•	•
TEMPERATURE RANGE			
Rated Performance	0 to +70°C	•	•
Operating	−25°C to +85°C	•	•
Storage	−55°C to +125°C	•	•
CASE SIZE	2" × 2" × 0.4" (51 × 51 × 10.2mm)	•	•

NOTES

*Specifications same as 2B30J/2B31J.
[1] [illegible]
[2] [illegible]
[3] Specifications referred to the unfiltered output at pin 1.
[4] [illegible]
[5] [illegible]
[6] [illegible]
[7] [illegible]
Specifications subject to change without notice.

OUTLINE DIMENSIONS

Dimensions shown in inches and (mm).

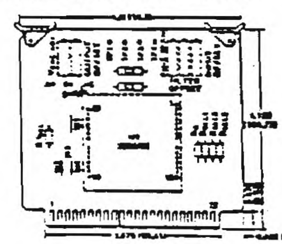


PIN DESIGNATIONS

PIN	FUNCTION	PIN	FUNCTION
1	OUTPUT (UNFILTERED)	16	EXC SEL 1
2	FINE GAIN (SPAN) ADJ.	17	+15V
3	FINE GAIN (SPAN) ADJ.	18	[illegible] OUT
4	FILTER OFFSET TRIM	19	[illegible] OUT
5	FILTER OFFSET TRIM	20	SENSE HIGH IN
6	BANDWIDTH ADJ. 1	21	EXC SEL 2
7	OUTPUT (FILTERED)	22	REF OUT
8	BANDWIDTH ADJ. 2	23	SENSE LOW IN
9	BANDWIDTH ADJ. 3	24	REGULATOR [illegible]
10	R_{GAIN}	25	REF IN
11	R_{GAIN}	26	[illegible]
12	−INPUT	27	[illegible]
13	INPUT OFFSET TRIM	28	COMMON
14	INPUT OFFSET TRIM	29	OUTPUT OFFSET TRIM
15	+INPUT		

[illegible]

AC1211/AC1213 MOUNTING CARDS



AC1211/AC1213 CONNECTOR DESIGNATIONS

PIN	FUNCTION	PIN	FUNCTION
A	[illegible]	1	EXC SEL 1
B	SENSE LOW IN	2	+15V
C	REF OUT	3	[illegible] OUT
D	REF IN	4	[illegible] OUT
E		5	SENSE HIGH IN
F		6	EXC SEL 2
H		7	OUTPUT OFFSET TRIM
J		8	
K	[illegible]	9	[illegible]
L	[illegible]	10	[illegible]
M		11	
N	COMMON	12	COMMON
P		13	
R	FINE GAIN ADJ.	14	
S	FINE GAIN ADJ.	15	
T	FILTER OFFSET TRIM	16	
U	FILTER OFFSET TRIM	17	R_{GAIN}
V	OUTPUT (FILTERED)	18	R_{GAIN}
W	−INPUT	19	OUTPUT (UNFILTERED)
X	INPUT OFFSET TRIM	20	BANDWIDTH ADJ. 1
Y	INPUT OFFSET TRIM	21	BANDWIDTH ADJ. 2
Z	+INPUT	22	BANDWIDTH ADJ. 3

The AC1211/AC1213 mounting card is available for the 2B30/2B31. The AC1211/AC1213 is an edge connector card with pin receptacles for plugging in the 2B30/2B31. In addition, it has provisions for installing the gain resistors and the bridge excitation, offset adjustment and filter cutoff programming components. The AC1211/AC1213 is provided with a Cinch 251-22-30-160 (or equivalent) edge connector. The AC1213 includes the adjustment pots; no pots are provided with the

Product Information

Scotchdamp

SJ2015X Viscoelastic Polymer
Types 110, 112, 113, 830
Material Damping Properties

Description:
SJ2015X designates a family of high energy dissipative polymers which when properly incorporated into a constrained layer damping system can afford excellent control of resonance-induced vibration problems.

Material damping properties are expressed as a complex number in which the dynamic shear modulus (G') is the real portion while the dimensionless quantity η (loss factor) is associated with the imaginary portion. Both these quantities interact to provide the polymer damping capacity. Density of all these polymers is 0.98 g/cm³ (0.035 lb/in³).

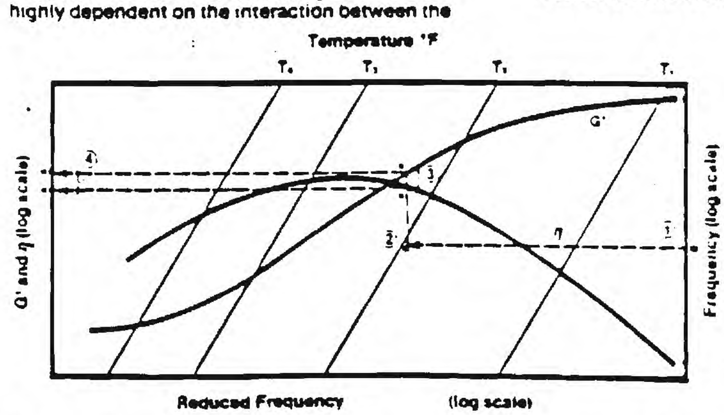
Discussion:
Both the dynamic shear modulus and the loss factor of these polymers are temperature and frequency dependent. When selecting a polymer for a constrained layer damping treatment, these variations in temperature and frequency must be taken into account. As a general rule, good constrained layer damping performance can be achieved when the polymeric components are chosen to insure that the inservice operation temperature frequency requirements over which the control is desired are between the 10^{-4} and 10^{4} region of the reduced frequency scale.

The performance of most damping devices are highly dependent on the interaction between the device and the system to which it is applied. A constrained layer control system is no different than a typical damping device and its ability to provide the desired performance is affected by parameters other than temperature and frequency. Namely the geometry, stiffness, mass, and resonance mode shape at the structure to which the control system is applied will affect the performance. For more details concerning the proper choice of constrained layer configuration, contact the Structural Products Department.

Data Interpolation:*
To determine the damping properties at the desired temperature and frequency from the following data graphs, proceed as follows:

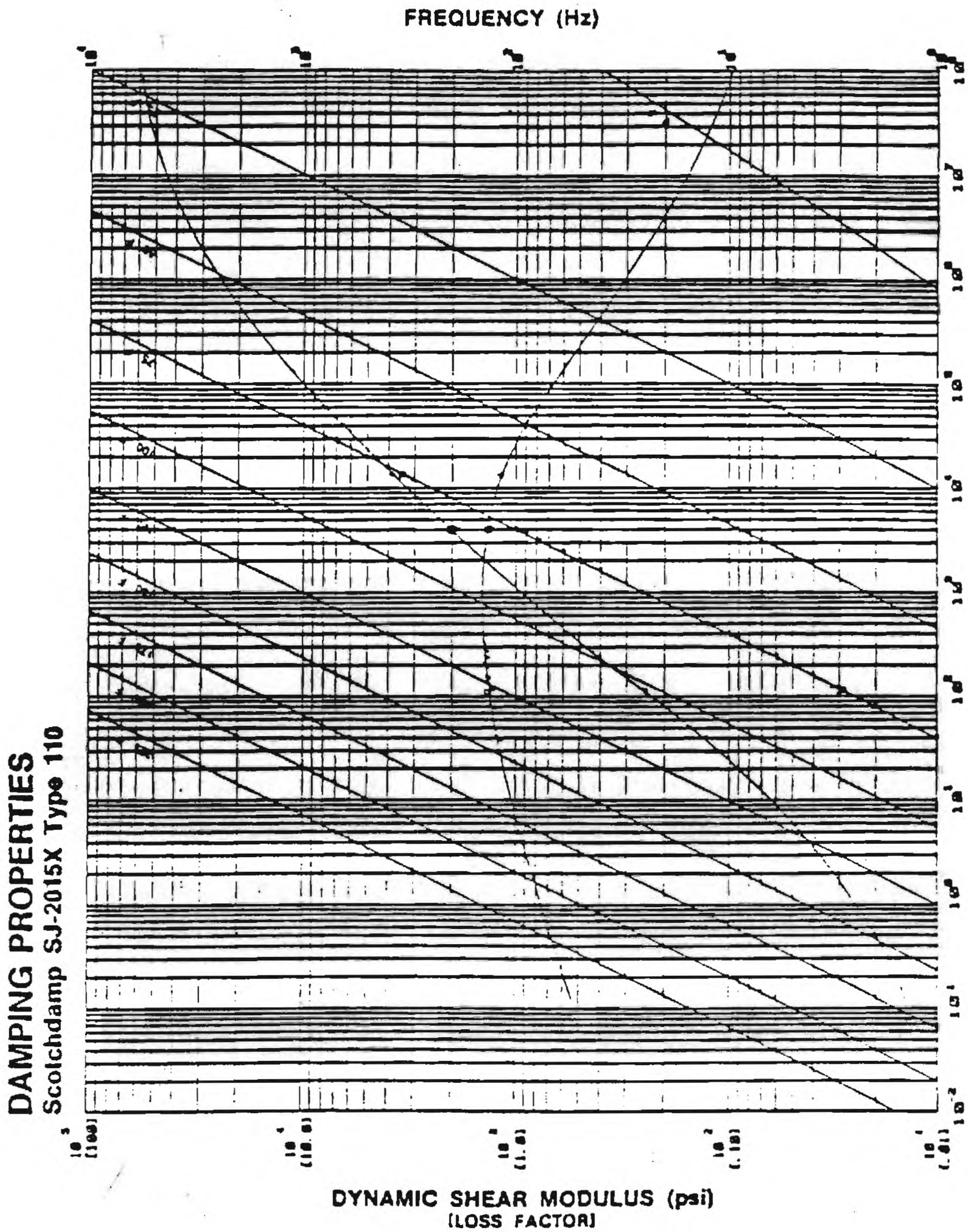
1. Locate the desired frequency on the right vertical scale.
2. Follow the chosen frequency line to the desired temperature isotherm.
3. From this intersect, go vertically up and/or down until crossing both the modulus and loss factor curves.
4. Read these modulus and loss factor values from the appropriate left vertical scale.

See sequenced example numbered below:



Caution:
The oblique constant temperature lines are separated by non-uniform spacings. Hence a linear extrapolation of temperature not explicitly shown cannot be used to obtain other temperature data.

*Note: The material damping properties are in the "reduced temperature format". This format is being considered by the American National Standards Institute for acceptance as a standard form of expressing the damping properties of linear polymers. Further information concerning this proposed standard is available from the ANSI S2-73 committee or the Structural Products Department of 3M.


DAMPING PROPERTIES
Scotchdamp SJ-2015X Type 110
FREQUENCY (Hz)
DYNAMIC SHEAR MODULUS (psi)
[LOSS FACTOR]

Appendix E

ELECTRONIC HARDWARE

(See p. 34 for Signal Flow Diagram)

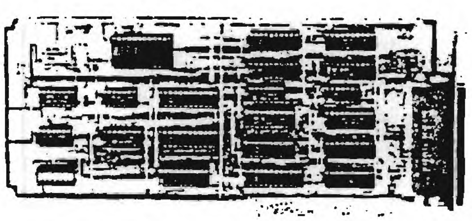
ELECTRONIC HARDWARE

DT2801-A:	16 X 12- bit A/D CONVERTER 2 X 12- bit D/A CONVERTER 16 X 12- bit DIGITAL I/O 27,500 bps WITH DMA STRAIN GAUGE INPUT BASE MOTOR OUTPUT
PDMA-16:	350,000 bps MAXIMUM WITH DMA ENCODER INPUTS 32 bit PROGRAMMABLE TIMER (0.002 Hz. to 10 MHz.)
DAC-02:	2 X 8-bit D/A CONVERTER ELBOW AND VERTICAL MOTOR OUTPUT
6801 BOARD:	6801 IN MODE 2 128-byte INTERNAL RAM PROGRAM IN 2716 2K EPROM 3 X HCTL-2000 QUADRATURE DECODERS

MBC MetraByte Corporation

DATA ACQUISITION AND CONTROL FOR IBM PC/XT/AT AND COMPATIBLE COMPUTERS

PDMA-16 VERY HIGH SPEED PARALLEL DIGITAL INTERFACE BOARD



FEATURES

- FREE SOFTWARE DRIVER greatly simplifies programming
- 16 or 8 bit digital transfers
- Transfer up to 250,000 bytes per second
- Internally clock driven or external triggering
- DMA, interrupt, or program controlled transfers

APPLICATIONS

- Interfaces to High-Speed peripherals
- High-Speed memory transfers from other computers
- Digital I/O control
- Printer/Plotter interfaces
- Interface to external High Speed A/D and D/A converters

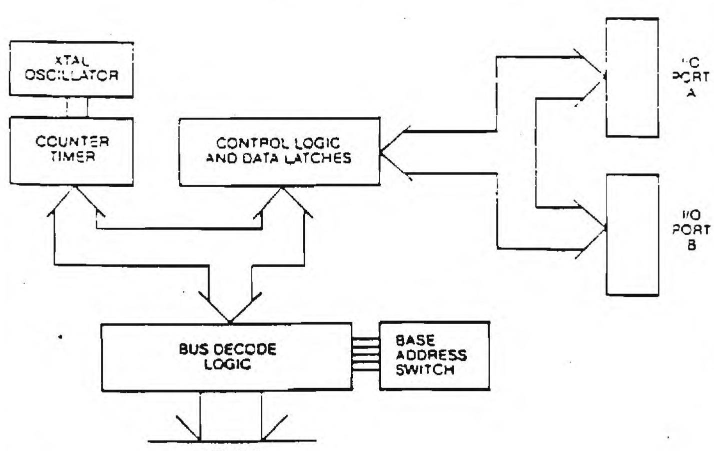
FUNCTIONAL DESCRIPTION

The PDMA-16 is a high speed 16 bit digital input/output interface board for the IBM PC/XT/AT. The board has 8 or 16 bit direct memory access capability (DMA). It is intended for applications requiring high speed digital memory transfers to and/or from external computers and peripheral devices.

Data transfer rates of 250,000 bytes/sec (or 125,000 words/sec.) may be attained on the standard 4.77MHz 8088 based P.C. and higher speeds may be obtainable on 8088-2, 8086, and 80286 based machines. Normal processor I/O transfers may also be made through the data ports. An on-board counter/timer allows the user to set data transfer rates, or the transfer may be triggered externally. All external connections are made through a 37 pin "D" connector that extends out the rear of the computer. Field wiring can be greatly simplified with the addition of an STA-U screw terminal board.

The PDMA-16 comes complete with a BASIC callable software driver (including source code) which greatly simplifies programming. The driver allows the user to perform DMA controller setup, timer setup and data block transfers. Source code is provided allowing the driver to be modified to run with upper level languages. It is also possible to write equivalent routines in other languages.

BLOCK DIAGRAM



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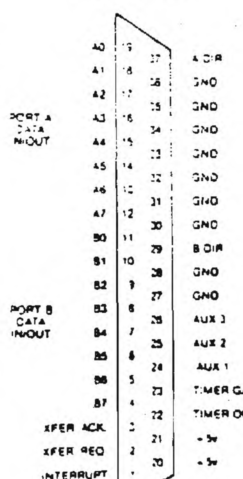
CONNECTOR PIN ASSIGNMENT



TECHNICAL DESCRIPTION

The DMA-16 provides the following functions —

1. Two 8 bit I/O ports, A & B. Each port can be set as an input or output under software control. The ports can be addressed as normal I/O locations using programmed transfer, or via the P.C. 8237 DMA controller. DMA transfers may be 8 bit (byte) through the A port only, or 16 bit (word) using both the A and B ports. In word mode, double buffering provides simultaneous update of the A and B ports on output. Regardless of DMA operation, both ports are addressable at any time as normal I/O locations. Two external signals, A DIRECTION and B DIRECTION provide information on the current direction of the ports.

2. DMA transfers may be initiated by an external signal (XFER REQUEST) or by an internal timer. The internal timer consists of a 10MHz xtal oscillator divided through 2 sections of an 8254 counter. This provides a clock rate ranging from 2.5MHz to 0.0023Hz (about 8 pulses/hr.). The choice of external signal or internal clock is via software control. On receipt of a positive edge on the XFER REQUEST input, the XFER ACKNOWLEDGE output goes low. Completion of the transfer to/from memory is acknowleged by the XFER ACKNOWLEDGE output returning to the high state. The operating DMA level is selectable as either Level 1 or 3 under software control. The user is required to set up the 8237 DMA controller on the P.C. system board before a transfer. A BASIC callable subroutine is provided to do this.

3. An interrupt channel is also provided. Software control allows you to select the active interrupt level (2-7), and choose between a positive or negative edge external interrupt on the INTERRUPT pin, an interrupt from the internal timer or a terminal interrupt generated by the 8237 DMA controller.

4. 3 auxiliary output bits, AUX 1-AUX 3, are available from the DMA and Interrupt control registers for general control functions.

PROGRAMMING

Programming the PDMA-16 in BASIC is very simple using the free software driver. The driver takes care of all board and PC initialization as well as controlling the actual data transfer. Source code for the BASIC driver is included and can be modified to be linked to other upper level languages or assembly code. For those not wishing to use the supplied software the I/O structure is very simple and fully specified. The structure of the board is described briefly below and in detail in the PDMA-16's user manual.

REGISTER FUNCTIONS

PORT A

Port A data corresponds directly to the data bus. In word mode, Port A is the least significant byte.

D7	D6	D5	D4	D3	D2	D1	D0
A7	A6	A5	A4	A3	A2	A1	A0

PORT B

Port B data corresponds directly to the data bus. In word mode, Port B is the most significant byte.

D7	D6	D5	D4	D3	D2	D1	D0
B7	B6	B5	B4	B3	B2	B1	B0

DMA CONTROL

The DMA control register bits have the following functions:—

D7	D6	D5	D4	D3	D2	D1	D0
DMA ENABLE	DMA LEVEL	AUX2	AUX1	XFER SOURCE	BYTE /WORD	B DIR.	A DIR.
0 = Disabled 1 = Enabled	0 = Level 1 1 = Level 3			0 = External (XFER REQ) 1 = internal 8254 timer	0 = byte 1 = word		

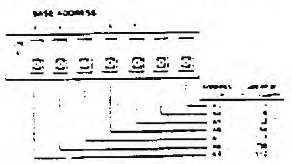
INTERRUPT CONTROL

The interrupt control register bits have the following functions:—

D7	D6 D5 D4	D3	D2 D1	D0
INT ENABLE	INTERRUPT LEVEL	AUX3	INT SOURCE	SLOPE
0 = Disabled 1 = Enabled	000 = Inactive 001 = Inactive 010 = Level 2 011 = Level 3 100 = Level 4 101 = Level 5 110 = Level 6 111 = Level 7		00 = External input 01 = 8237 terminal 10 = 8254 timer 11 = 8237 terminal	0 = + edge 1 = − edge

I/O MAP

The DMA-16 uses 8 consecutive locations in I/O address space (this does not interfere with memory addressing in any way). The BASE ADDRESS is set by a 7 position DIP switch and can be on any 8 bit boundary in the decoded address range of 0 to 3F8 hex. (normal useable range is 100-3F8H). An example of setting the BASE ADDRESS switch is shown below.



SWITCHES HAVE DECIMAL VALUES AS ABOVE IN THE "OFF" POSITION. IN THE "ON" POSITION DECIMAL VALUE IS ZERO.

The addresses are mapped as follows:—

ADDRESS	FUNCTION	TYPE
BASE + 0	A port	R/W
+ 1	B port	R/W
+ 2	DMA control	R/W
+ 3	Interrupt control	R/W
+ 4	Counter 0	R/W
+ 5	Counter 1	R/W
+ 6	Counter 2	R/W
+ 7	Control	W
	Status	R

(R = read, W = write)

Note that the first 4 addresses correspond to the digital I/O and control, and the last 4 addresses correspond to the 8254 timer.

SPECIFICATIONS

DATA TRANSFER RATE	0 to 125,000 WORDS (16 bit) per second
	0 to 250,000 BYTES (8 bit) per second
LOGIC LEVELS	Fully TTL compatible on both inputs and outputs
Input High Voltage	2.0 V min.
Input Low Voltage	.8 V max.
Output High Voltage	2.4 V min.
Output Low Voltage	.5 V max.

POWER SUPPLIES

+ 5 volt	850 mA typ. 1 mA max
+ 12 volt	not used
− 12 volt	not used

PHYSICAL

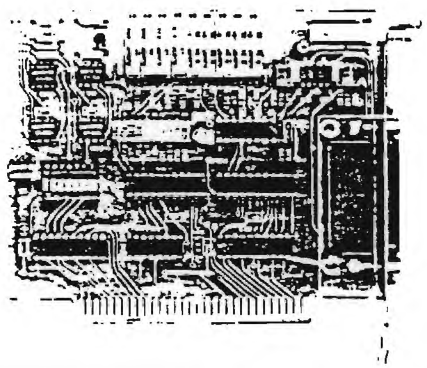
Size	2/3 slot, will not fit in XT "half" slots
Operating Temp.	0 to 60 Degrees C
Storage Temp.	− 40 to + 100 Degrees C.

THE PRICE ***$295.00***

MBC MetraByte Corporation

DATA ACQUISITION AND CONTROL FOR IBM PC/XT/AT AND COMPATIBLE COMPUTERS

12 BIT TWO CHANNEL ANALOG OUTPUT BOARD MODEL DAC-02



FEATURES

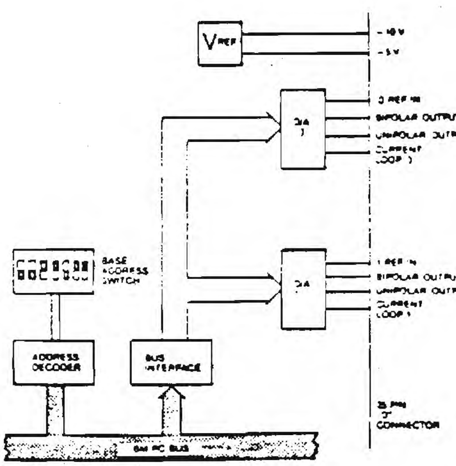
- 2 Analog Output Channels
- 12 Bit Resolution
- +5, +10, ±5, ±10 V Output Ranges
- 4-20 mA Current Loop Capability
- Plugs Directly Into The IBM PC
- Calibration Software Included

APPLICATIONS

- Servo Control
- Programmable Amplifier
- 12 Bit Resolution Voltage Source
- Function Generator

BLOCK DIAGRAM

DAC02



IBM IS A REGISTERED TRADEMARK OF INTERNATIONAL BUSINESS MACHINES INC

FUNCTIONAL DESCRIPTION

The DAC-02 consists of 2 separate double buffered 12 bit multiplying D/A channels plus interface circuitry. The D/A converters may be used with a fixed D.C. reference as conventional D/A's. On board references of −5 v and −10 v provide output ranges of 0–5 v, 0–10 v, ±5 v and ±10 v and 4–20 mA for process control current loops. Alternatively, the D/A's may be operated with a variable or A.C. reference signal as multiplying D/A's, the output is the product of reference and digital inputs. With an A.C. reference, the unipolar outputs provide 2 quadrant multiplication and the bipolar outputs provide 4 quadrant operation. 12 bit accuracy is maintained up to 1 KHz.

Since data is 12 bits, data is written to each D/A in 2 consecutive bytes. The first byte is the least significant and contains the 4 least significant bits of data (see Data Format section). The second byte is the most significant and contains the most significant 8 bits of data. The least significant byte is usually written first and is stored in an intermediate register in the D/A, having no effect on the output. When the most significant byte is written, its data is added to the stored least significant data and presented "broadside" to the D/A converter thus assuring a single step update. This process is known as double buffering.

A floppy Disk comes with this board which contains a Calibration Program for adjusting the various ranges on the board. It actually draws a picture of the board and points to the appropriate potentiometer for adjustment. An Installation program also illustrates the base address switch settings based on the Decimal or "Hex" value entered. Finally, a fully documented program which desribes in detail the simple steps needed to program the DAC-02. The board uses the OUT command in basic.

The DAC-02 is packaged on a 5" long "half-slot" board suitable for use in all models of IBM P.C.'s (including the portable) and all compatibles including the T.I. Professional. The DAC-02 is addressed as an I/O device using 8 I/O locations and may have its I/O address set by means of an on-baord DIP switch to any 8 bit boundary in the 255–1023 (decimal) I/O address space. The board uses the internal +5 v, +12 v and −12 v computer supplies and consumes 850 milli-watts of power.

PROGRAMMING

ftware is provided with the DAC-02 as programming is simple with I/O instructions in whatever application language is used.
following example shows how to output data in BASIC. It is readily adaptable to other languages. Since the D/A's have 12 bit resolution should be in the range 0- 4095 decimal. First split the data into 2 bytes (low) and DH% (high) -

```
00 DH% = INT(D/16)      'generate high byte
10 DL% = D - 16*DH%     'derive remainder in low byte
20 DL% = 16 * DL%       'shift low nybble 4 places left
```

ite the data to the D/A. The example assumes D/A #0 with a board dress of Hex 300 -

```
30 OUT &H300, DL%       'low byte
40 OUT &H301, DH%       'high byte and load
```

An assembly language routine is even simpler. Assume AX contains the data and DX has the board I/O address. To write to D/A #0 -

```
MOV CL,4          ;set up for 4 left shifts
SAL AX,CL         ;left justify data
OUT DX,AX         ;write to D/A #0
```

The following program in BASIC illustrates how a DAC02 can output a voltage or current sine depending on the value of D.
Substituting line 10 for a value proportional to measurement and control parameters obtained by other metrabyte boards is easy.

```
10 INPUT "Enter the data from 0 to 4095 ";D
20 DH% = INT(D/16)
30 DL% = D - 16*DH%
40 DL% = 16*DL%                BASE ADDRESS
50 OUT &H330,DL%               OF BOARD IS
60 OUT &H331,DH%               &H330
70 GOTO 10
```

AP

DAC-02 requires 8 consecutive addresses in I/O address . The locations of the D/A registers is as follows -

SE ADDRESS	+0	-	D/A #0 LOW BYTE
" "	+1	-	D/A #0 HIGH BYTE
" "	+2	-	D/A #1 LOW BYTE
" "	+3	-	D/A #1 HIGH BYTE

next 4 addresses are redundant and repeat the above pat- and can be ignored in programming:-

SE ADDRESS	+4	-	D/A #0 LOW BYTE
" "	+5	-	D/A #0 HIGH BYTE
" "	+6	-	D/A #1 LOW BYTE
" "	+7	-	D/A #1 HIGH BYTE

DATA FORMAT

Data format for the D/A registers is as follows:-

	D7	D6	D5	D4	D3	D2	D1	D0
LOW BYTE: BASE + 0 OR 2	B9	B10	B11	B12 (LSB)	x	x	x	x

(x = DON'T CARE)

	D7	D6	D5	D4	D3	D2	D1	D0
HIGH BYTE: BASE + 1 OR 3	B1 (MSB)	B2	B3	B4	B5	B6	B7	B8

Writing the low byte stores it in an intermediate register. Writing the high byte loads the D/A with both the high byte and the stored low byte data. For 8 bit operation, first write zero to the low byte and all further operations may then be performed with the high byte only.

Assembly language programmers should note that if data is left justified, 16 bit output operations may be used (e.g. OUT DX, AX) as the data sequence is conventional Intel Low/High byte.

ECTING OUTPUT RANGES

operating output range is selected by jumpering pins on the rear connector mating half. The various ranges are selected as follows:-

NGE		JUMPER PINS	OUTPUT
+5 v	D/A #0:	21 to 22	Pin 24
	D/A #1:	15 to 16	Pin 18
+10 v	D/A #0:	20 to 22	Pin 24
	D/A #1:	14 to 16	Pin 18
±5 v	D/A #0:	21 to 22	Pin 23
	D/A #1:	15 to 16	Pin 17
±10 v	D/A #0:	20 to 22	Pin 23
	D/A #1:	14 to 16	Pin 17
4-20 mA	D/A #0:	21 to 22	Pin 25
	D/A #1:	15 to 16	Pin 19
A.C. Ref.	D/A #0:	Input on pin 22	Pin 24 (2 quadrant) Pin 23 (4 quadrant)
	D/A #1:	Input on pin 16	Pin 18 (2 quadrant) Pin 17 (4 quadrant)

For unipolar outputs 0 - 5 v, 0 - 10 v and 4-20 mA, data coding is true binary. Due to the analog inversion in the bipolar output ranges, ±5 v and ±10 v data coding is complementary offset binary i.e. zero digital corresponds to + Full Scale analog and 4095 digital corresponds to − Full scale analog.

EXAMPLE: UNIPOLAR 0 to +5 V	DECIMAL	VOLTS
	0	0 V
	1024	1.25 V
	2048	2.50 V
	4096	5.00 V

BIPOLAR −10 V to +10 V	DECIMAL	VOLTS
	0	+10.0 V
	1024	+5.0 V
	2048	0 V
	4095	−10.0 V

USE WITH A.C. REFERENCE (DIGITAL ATTENUATOR)

Apart from its uses as a standard D.C. output D/A, the DAC-02 can be used with a bipolar or A.C. reference signal.

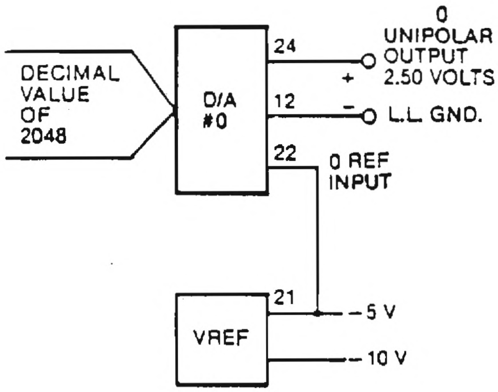
With an A.C. reference, the customary terminology of operation is somewhat different. If the output is taken from the unipolar outputs, 2 quadrant operation is obtained since the reference which may be positive or negative is multiplied with a positive only digital signal. If the output is taken from the bipolar output, the offset digital input can effectively be positive or negative which together with the possible positive or negative states of the reference results in 4 quadrant operation.

Two other parameters are of interest in A.C. operation. The first is feedthrough, the amount of residual signal at digital zero. The feedthrough which is mainly a function of stray capacitance rises with frequency. At 10KHz it is typically 5 mV peak - peak with a ±5 v reference. The second parameter that is a limit at a lower frequency, is the accuracy/frequency characteristic. Due to distributed capacitance in the R-2R ladder network, the full 12 bit performance of the D/A falls off as the frequency rises. Above about 1 KHz the dynamic performance of the D/A will be less than 12 bit accurate.

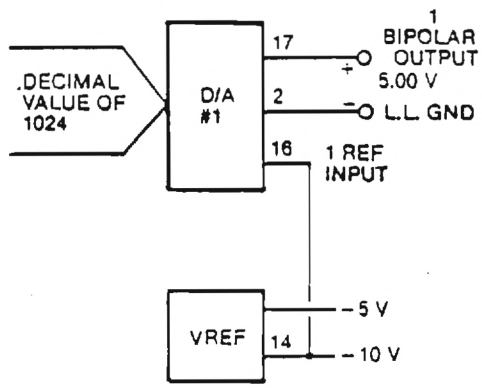
The DAC-02 will perform well in synchro-digital and resolver applications for sine/cosine generation with 400 Hz reference.

$T_{set} = 1.5\ \mu s$
~600 kHz
DAC 7548

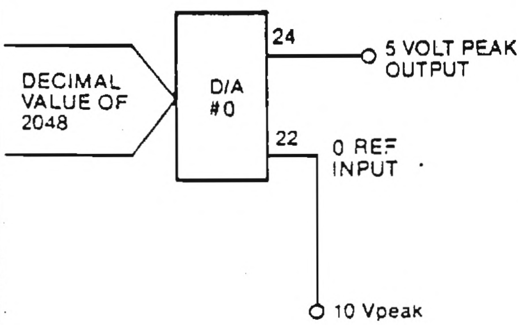
UNIPOLAR OPERATION
D/A #0 (0 to +5 V)



BIPOLAR OPERATION
D/A #1 (± 10 V)



AC OPERATION
DA #0 (UNIPOLAR OUTPUT)

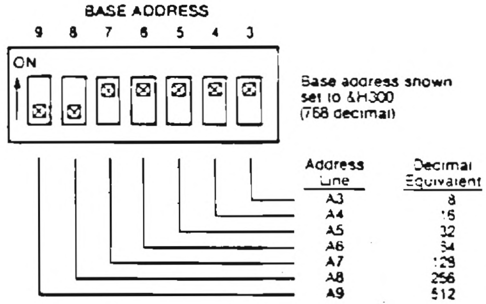


BASE ADDRESS SWITCH

The base address is set by a 7 position DIP switch and can in theory be placed anywhere in I/O address space, but base addresses below FF hex (255 decimal) should be avoided as this address range is used by the internal I/O of the computer. The 200-3FF hex (512-1023) address range provides extensive unused areas of I/O space, though you should check with page 2-23 of the "Technical Reference Manual" for possible conflicts with commonly installed peripherals.

Unless you are using the IBM prototype board which uses addresses in the range 300-31F hex, a simple choice of base address for the DAC-02 would be 300 hex. The DAC-02 board will then occupy I/O addresses 300-307. The setting for the BASE ADDRESS switch is shown below:

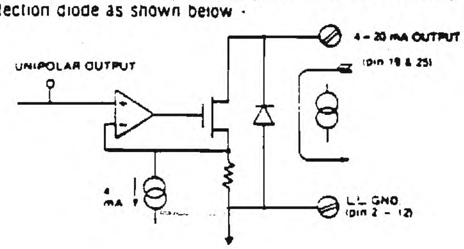
BASE ADDRESS SWITCH SETTING



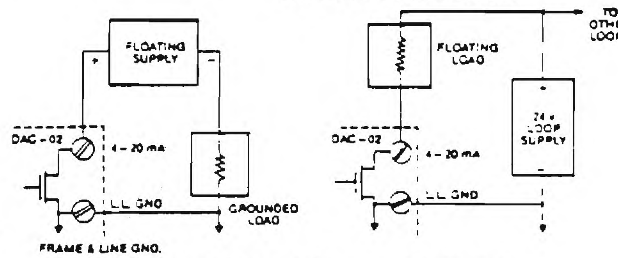
Note that a switch in the ON position corresponds to a zero, and in the OFF position corresponds to the binary weight of the corresponding address bit (512, 256, 128, 64, 32, 16, 8). The base I/O address is the sum of all the OFF switch address bits.

4-20 mA CURRENT LOOP OUTPUT

The 4 – 20 mA current loop output consists of a precision current sink formed by a VMOS power F.E.T. and reverse protection diode as shown below :-



A minimum voltage of 3 volts must be maintained across this output circuit to insure correct operation. The maximum voltage should not exceed 36 volts for power dissipation reasons. A 24 v or 36 v loop supply is ideal. There are 2 ways of connecting the process loop, grounded load with floating supply or floating load with grounded supply. Obviously the second method allows many loops to be powered by the same supply but constrains the load to be 2 wire floating. The alternative connections are shown below:-



A DECIMAL VALUE OF 0 = 4 mA. A DECIMAL VALUE OF 4095 = 20 mA.

CONNECTOR PIN ASSIGNMENTS

A rear view of the 25 pin D connector is shown below. The DAC-02 board has a female DB25 socket and a DB25P solder cup plug is required to make connections (MetraByte part # SMC-25). Usually only 3 or 4 wires (D/A outputs and ground) will be required for connections, so that a multi-wire flat cable is not required. (Note: 25 pin D connectors are identical to RS-232C connectors). Output range selection is controlled by jumpering pins on the plug body as described in the Section entitled "Selecting Output Ranges."

	Pin	Pin	
DIG. COM.	1		
		14	– 10 v. REFERENCE
LOW LEVEL GROUNDS	2		
		15	– 5 v. REFERENCE
	3		
		16	D/A #1 REFERENCE INPUT
	4		
		17	D/A #1 BIPOLAR OUTPUT
	5		
		18	D/A #1 UNIPOLAR OUTPUT
	6		
		19	D/A #1 4 – 20 mA OUTPUT
	7		
		20	– 10 v. REFERENCE
	8		
		21	– 5 v. REFERENCE
	9		
		22	D/A #0 REFERENCE INPUT
	10		
		23	D/A #0 BIPOLAR OUTPUT
	11		
		24	D/A #0 UNIPOLAR OUTPUT
	12		
		25	D/A #0 4 – 20 mA OUTPUT
+ 5 v (*)	13		

* 5 v power from the computer is supplied on Pin 13. If you use this power avoid shorting or overloading of the computer power supply.

SPECIFICATIONS

POWER SUPPLIES

+ 5 v supply:	75 mA typ., 100 mA max.
– 5 v supply:	Not used
+ 12 v supply:	15 mA typ., 25 mA max.
– 12 v supply:	25 mA typ., 35 mA max.
Total power dissipation:	0.85 watt typical.

OUTPUT RANGES

Channels:	2
I/O address:	DIP switch selected on any 8 bit boundary.
Resolution:	12 bits (1 part in 4095)
Relative accuracy:	1/2 LSB (0.01%) max.
Differential linearity:	1/2 LSB max.
Fixed reference ranges:	0 to + 5 v (unipolar) 0 to + 10 v (unipolar) ± 5 v (bipolar) ± 10 v (bipolar) 4 – 20 mA current loop
Variable reference ranges:	± 10 v (2 or 4 quadrant)
Reference input resistance:	7K ohm min., 11K ohm typ., 20K ohm max.
Voltage output impedance:	< 0.1 ohm max.
Voltage output drive current:	± 5 mA min.
4 – 20 mA compliance (for current loop):	3 – 36 v

ENVIRONMENTAL

Temperature coefficient:	± 25 ppM/deg.C. (with reference)
of gain	± 5 ppM/deg C. (external ref.)
Zero drift:	± 3 ppM/deg.C.
Operating temperature	0 – 70 deg.C.
Storage temperature:	– 55 to + 125 deg.C.
Humidity:	0 – 95% non-condensing
Weight:	4 oz. (120 g)

THE PRICE $250.00

HEWLETT PACKARD

QUADRATURE DECODER/ COUNTER INTERFACE IC

HCTL-2000

TECHNICAL DATA OCTOBER 1985

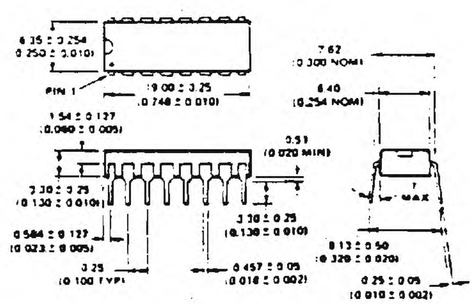
Features

- FULL FUNCTION IN A SPACE SAVING PACKAGE
- SUBSTANTIALLY REDUCED SYSTEM SOFTWARE
- FULL 4X DECODE
- HIGH NOISE IMMUNITY:
  SCHMITT TRIGGER INPUTS
  DIGITAL NOISE FILTER
- 8 BIT TRISTATE INTERFACE
- 12 BIT BINARY UP/DOWN COUNTER TO BUFFER THE CONTROL PROCESSOR
- 12 BIT LATCH AND INHIBIT LOGIC PROVIDE A STABLE, 2 BYTE READ OPERATION
- 8 AND 12 BIT OPERATING MODES

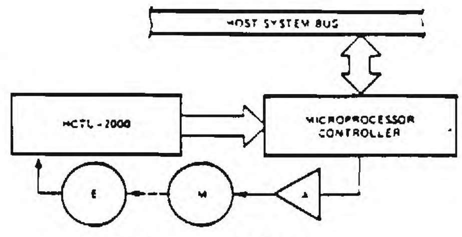
Description

The HCTL-2000 is an HCMOS IC that performs the quadrature decoder, counter, and bus interface function. The HCTL-2000 is designed to improve system performance in digital closed loop motion control systems and digital data input systems. It does this by shifting time intensive quadrature decoder functions to a cost effective hardware solution. The HCTL-2000 consists of a 4x quadrature decoder, 12 bit binary up/down state counter, and 8 bit bus interface. The use of Schmitt triggered CMOS inputs and a 3 bit state delay filter allows reliable operation in noisy environments. The HCTL-2000 provides LSTTL compatible tri-state output buffers. Operation is specified for a temperature range from -40 to +85°C at clock frequencies up to 3.9 MHz.

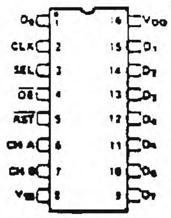
Package Dimensions



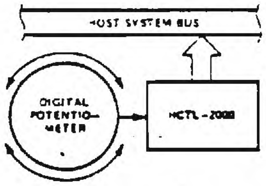
LEAD FINISH: SOLDER DIPPED



DIGITAL MOTION CONTROL



PINOUT



DIGITAL DATA ENTRY

Applications

- INTERFACE QUADRATURE INCREMENTAL ENCODERS TO MICROPROCESSORS
- INTERFACE DIGITAL POTENTIOMETERS TO DIGITAL DATA INPUT BUSSES

Table of Contents

ESD WARNING: HCTL-2000 is implemented in a standard HCMOS process with diode protection of all I/O pads. Standard precautions for handling HCMOS devices should be observed.

Operating Characteristics

Table 1. Absolute Maximum Ratings all voltages below are referenced to V_{ss}

Parameter	Symbol	Limits	Units
DC Supply Voltage	V_{dd}	−0.3 to +7	V
Input Voltage	V_{in}	−0.3 to V_{dd} +0.3	V
Storage Temperature	T_s	−40 to +125	°C
Operating Temperature	T_a [1]	−40 to +85	°C

Table 2. Recommended Operating Conditions

Parameter	Symbol	Limits	Units
DC Supply Voltage	V_{dd}	+3 to +6	V
Ambient Temperature	T_a [1]	−40 to +85	°C

Table 3. DC Characteristics $V_{dd} = 5V \pm 5\%$, T_a = −40 to +85°C

Symbol	Parameter	Condition	Min.	Typ.	Max.	Unit
V_{il} [2]	Low-Level Input Voltage				1.5	V
V_{ih} [2]	High-Level Input Voltage		3.5			V
V_{t+} [2]	Schmitt-Trigger Positive-Going Threshold			3.0	4.0	V
V_{t-} [2]	Schmitt-Trigger Negative-Going Threshold		1.0	1.5		V
V_h	Schmitt-Trigger Hysteresis		1.0	1.5		V
I_{in}	Input Current	$V_{in} = V_{dd}$ $V_{in} = V_{ss}$	−10 −10	1 1	+10 −10	μA μA
V_{oh} [2]	High-Level Output Voltage	I_{oh} = −1.6mA	2.4	4.5		V
V_{ol} [2]	Low-Level Output Voltage	I_{ol} = +1.6mA		0.2	0.4	V
I_{oz}	High-Z Output Leakage Current	$V_o = V_{ss}$ or V_{dd}	−10	1	+10	μA
I_{dd}	Quiescent Supply Current	$V_{in} = V_{ss}$ or V_{dd} V_o = HiZ		50		μA
C_{in}	Input Capacitance	Any Input [3]		5		pF
C_{out}	Output Capacitance	Any Output [3]		7		pF

NOTES:

1. Free Air
2. In general, for any V_{dd} between the allowable limits +3V to +6V, V_{il} = 0.3V_{dd} and V_{ih} = 0.7V_{dd}. V_{t+} and V_{t-} vary as Fig 1. $V_{oh} = V_{dd}$ − 0.5V and V_{ol} = V_{ss} + 0.2V @ [illegible] 1.6 ma respectively.
3. Excluding package capacitance.

MOTOROLA

SN54LS221
SN74LS221

DUAL MONOSTABLE MULTIVIBRATORS WITH SCHMITT-TRIGGER INPUTS

LOW POWER SCHOTTKY

DESCRIPTION — Each multivibrator of the LS221 features a negative-transition-triggered input and a positive-transition-triggered input either of which can be used as an inhibit input.

Pulse triggering occurs at a voltage level and is not related to the transition time of the input pulse. Schmitt-trigger input circuitry for B input allows jitter-free triggering for inputs as slow as 1 volt/second, providing the circuit with excellent noise immunity. A high immunity to V_{CC} noise is also provided by internal latching circuitry.

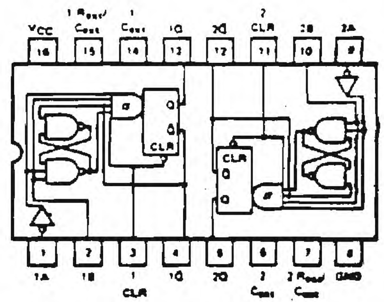
Once triggered, the outputs are independent of further transitions of the inputs and are a function of the timing components. The output pulses can be terminated by the overriding clear. Input pulse width may be of any duration relative to the output pulse width. Output pulse width may be varied from 35 nanoseconds to a maximum of 70 s by choosing appropriate timing components. With $R_{ext} = 2\ k\Omega$ and $C_{ext} = 0$, a typical output pulse of 30 nanoseconds is achieved. Output rise and fall times are independent of pulse length.

Pulse width stability is achieved through internal compensation and is virtually independent of V_{CC} and temperature. In most applications, pulse stability will only be limited by the accuracy of external timing components.

Jitter-free operation is maintained over the full temperature and V_{CC} ranges for greater than six decades of timing capacitance (10pF to 10 μF), and greater than one decade of timing resistance (2 to 70 kΩ for the SN54LS221, and 2 to 100 kΩ for the SN74LS221). Pulse width is defined by the relationship: $t_W(out) = C_{ext}R_{ext}\ \ln 2 \approx 0.7\ C_{ext}R_{ext}$. If pulse cutoff is not critical, capacitance up to 1000 μF and resistance as low as 1.4 kΩ may be used. The range of jitter-free pulse widths is extended if V_{CC} is 5 V and 25°C temperature.

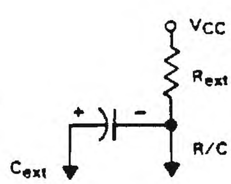
- SN54LS221 and SN74LS221 IS A DUAL HIGHLY STABLE ONE-SHOT
- OVERRIDING CLEAR TERMINATES OUTPUT PULSE
- PIN OUT IS IDENTICAL TO SN54LS/74LS123

(TOP VIEW)



positive logic: Low input to clear resets Q low and $\bar{Q}$ high regardless of d-c levels at A or B inputs

J Suffix — Case 620-08 (Ceramic)
N Suffix — Case 648-05 (Plastic)



FUNCTION TABLE

(EACH MONOSTABLE)

INPUTS			OUTPUTS	
CLEAR	A	B	Q	$\bar{Q}$
L	X	X	L	H
X	H	X	L	H
X	X	L	L	H
H	L	↑	⎍	⎍̄
H	↓	H	⎍	⎍̄
↑	L	H	⎍	⎍̄

TYPE	TYPICAL POWER DISSIPATION	MAXIMUM OUTPUT PULSE LENGTH
SN54LS221	23 mW	49 s
SN74LS221	23 mW	70 s

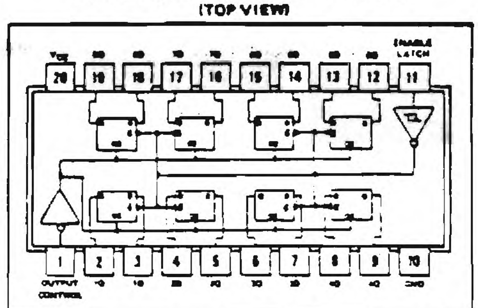
TTL
MSI

TYPES SN54LS373, SN54LS374, SN54S373, SN54S374, SN74LS373, SN74LS374, SN74S373, SN74S374
OCTAL D-TYPE TRANSPARENT LATCHES AND EDGE-TRIGGERED FLIP-FLOPS

BULLETIN NO. DL-S 12350, OCTOBER 1975 – REVISED JUNE 1979

- Choice of 8 Latches or 8 D-Type Flip-Flops In a Single Package
- 3-State Bus-Driving Outputs
- Full Parallel-Access for Loading
- Buffered Control Inputs
- Clock/Enable Input Has Hysteresis to Improve Noise Rejection
- P-N-P Inputs Reduce D-C Loading on Data Lines ('S373 and 'S374)
- SN54LS363 and SN74LS364 Are Similar But Have Higher V_{OH} For MOS Interface

SN54LS373, SN54S373 . . . J PACKAGE
SN74LS373, SN74S373 . . . J OR N PACKAGE
(TOP VIEW)

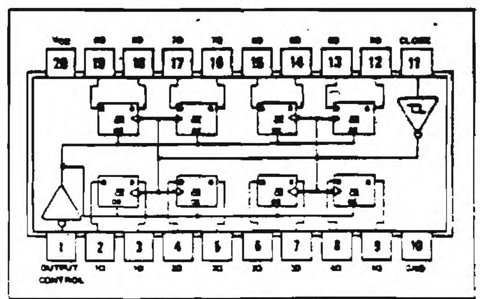


logic: see function table

'LS373, 'S373
FUNCTION TABLE

OUTPUT ENABLE	ENABLE LATCH	D	OUTPUT
L	H	H	H
L	H	L	L
L	L	X	Q_0
H	X	X	Z

SN54LS374, SN54S374 . . . J PACKAGE
SN74LS374, SN74S374 . . . J OR N PACKAGE
(TOP VIEW)



logic: see function table

'LS374, 'S374
FUNCTION TABLE

OUTPUT ENABLE	CLOCK	D	OUTPUT
L	↑	H	H
L	↑	L	L
L	L	X	Q_0
H	X	X	Z

See explanation of function tables on page 1-13.

description

These 8-bit registers feature totem-pole three-state outputs designed specifically for driving highly-capacitive or relatively low-impedance loads. The high-impedance third state and increased high-logic-level drive provide these registers with the capability of being connected directly to and driving the bus lines in a bus-organized system without need for interface or pull-up components. They are particularly attractive for implementing buffer registers, I/O ports, bidirectional bus drivers, and working registers.

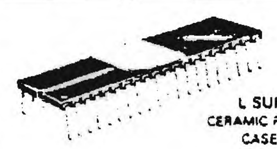
The eight latches of the 'LS373 and 'S373 are transparent D-type latches meaning that while the enable (G) is high the Q outputs will follow the data (D) inputs. When the enable is taken low the output will be latched at the level of the data that was set up.

MOTOROLA

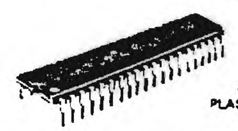
MC6801
MC6803

MOS
(N-CHANNEL, SILICON-GATE, DEPLETION LOAD)

MICROCOMPUTER
MICROPROCESSOR

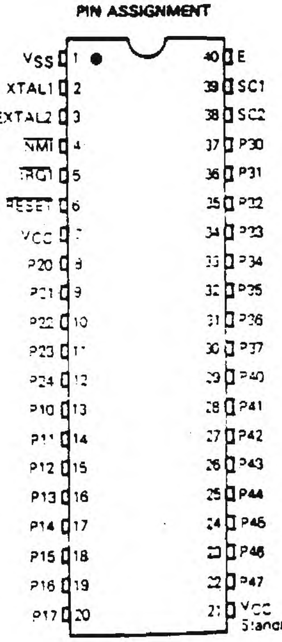


L SUFFIX
CERAMIC PACKAGE
CASE 715



P SUFFIX
PLASTIC PACKAGE
CASE 711

PIN ASSIGNMENT



MICROCOMPUTER/MICROPROCESSOR (MCU/MPU)

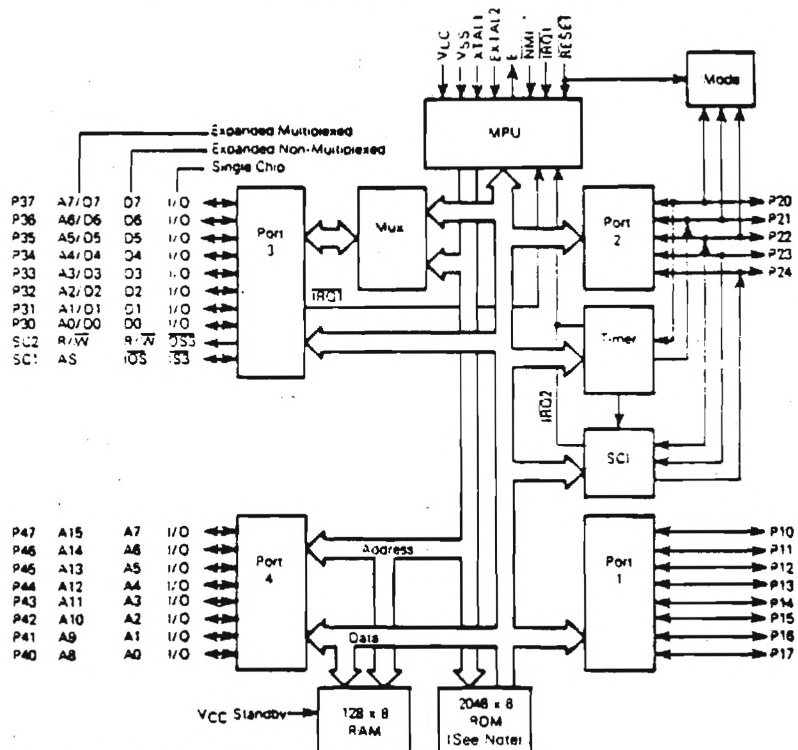
The MC6801 is an 8-bit single-chip microcomputer unit (MCU) which significantly enhances the capabilities of the M6800 Family of parts. It includes an upgraded M6800 microprocessor unit (MPU) with upward-source and object-code compatibility. Execution times of key instructions have been improved and several new instructions have been added including an unsigned multiply. The MCU can function as a monolithic microcomputer or can be expanded to a 64K byte address space. It is TTL compatible and requires one +5-volt power supply. On-chip resources include 2048 bytes of ROM, 128 bytes of RAM, a serial communications interface (SCI), parallel I/O, and a three-function programmable timer. The MC6803 can be considered as an MC6801 operating in modes 2 or 3. An EPROM version of the MC6801, the MC68701 microcomputer, is available for systems development. The MC68701 is pin and code compatible with the MC6801/03 and can be used to emulate the MC6801/03. The MC68701 is described in a separate Advance Information publication.

- Enhanced MC6800 Instruction Set
- 8 × 8 Multiply Instruction
- Serial Communications Interface (SCI)
- Upward Source and Object Code Compatibility with the M6800
- 16-Bit Three-Function Programmable Timer
- Single-Chip or Expanded Operation to 64K Byte Address Space
- Bus Compatibility with the M6800 Family
- 2048 Bytes of ROM (MC6801 Only)
- 128 Bytes of RAM
- 64 Bytes of RAM Retainable During Powerdown
- 29 Parallel I/O and Two Handshake Control Lines
- Internal Clock Generator with Divide-by-Four Output
- −40 to 85°C Temperature Range
- −40 to 105°C Temperature Range

GENERIC INFORMATION

Frequency MHz	Temperature	Generic Number: Ceramic Package L Suffix	Generic Number: Plastic Package P Suffix
1.0	0°C to 70°C	MC6801L1	MC6801P1
1.0	−40°C to 85°C	MC6801CL1	MC6801CP1
1.0	−40°C to 105°C	MC6801VL1	MC6801VP1
1.0	0°C to 70°C	MC6803L	MC6803P
1.0	−40°C to 85°C	MC6803CL	MC6803CP
1.0	−40°C to 105°C	MC6803VL	MC6803VP
1.25	0°C to 70°C	MC6801L1-1	MC6803P1-1
1.25	−40°C to 85°C	MC6801CL1-1	MC6803CP1-1
1.25	0°C to 70°C	MC6803L1	MC6803P1
1.25	−40°C to 85°C	MC6803CL-1	MC6803CP-1
1.5	0°C to 70°C	MC68A01L1	MC68A01P1
1.5	0°C to 70°C	MC68A03L	MC68A03P
2.0	0°C to 70°C	MC68B01L1	MC68B01P1
2.0	0°C to 70°C	MC68B03L	MC68B03P

FIGURE 1 — M6801 MICROCOMPUTER FAMILY BLOCK DIAGRAM



NOTE: No functioning ROM in MC6803

POWER CONSIDERATIONS

The average chip-junction temperature, T_J, in °C can be obtained from:

$$T_J = T_A + (P_D \bullet \theta_{JA}) \quad (1)$$

Where:

T_A ≡ Ambient Temperature, °C

θ_{JA} ≡ Package Thermal Resistance, Junction-to-Ambient, °C/W

P_D ≡ $P_{INT} + P_{PORT}$

P_{INT} ≡ $I_{CC} \times V_{CC}$, Watts — Chip Internal Power

P_{PORT} ≡ Port Power Dissipation, Watts — User Determined

For most applications $P_{PORT} \ll P_{INT}$ and can be neglected. P_{PORT} may become significant if the device is configured to drive Darlington bases or sink LED loads.

An approximate relationship between P_D and T_J (if P_{PORT} is neglected) is:

$$P_D = K \div (T_J + 273°C) \quad (2)$$

Solving equations 1 and 2 for K gives:

$$K = P_D \bullet (T_A + 273°C) + \theta_{JA} \bullet P_D^2 \quad (3)$$

Where K is a constant pertaining to the particular part. K can be determined from equation 3 by measuring P_D (at equilibrium) for a known T_A. Using this value of K the values of P_D and T_J can be obtained by solving equations (1) and (2) iteratively for any value of T_A.

Appendix F

SOFTWARE LISTINGS

SOFTWARE

DMA.PAS - PROGRAMS PDMA-16 FOR ENCODER INPUT

6801.ASM - READS AND HOLDS ENCODER VALUES
BEFORE SENDING TO PDMA-16

JOG.PAS - ALLOWS OPERATION OF ARM FROM IBM-PC
OPTIONS: set up controllers
move any joint
disable controllers
quit

```
program DMA;

const
  DMA_Command_Register:          Byte = $08;
  Mode_Register:                 Byte = $0B;
  Mask_Register:                 Byte = $0A;
  Address_Register_1:            Byte = $02;
  Address_Register_3:            Byte = $06;
  Byte_Count_Register_1:         Byte = $03;
  Byte_Count_Register_3:         Byte = $07;
  Page_Register_1:               Byte = $83;
  Page_Register_3:               Byte = $82;
  Port_A:                        Integer = $0308;
  Port_B:                        Integer = $0309;
  DMA_Control_Register:          Integer = $030A;
  Interrupt_Control:             Integer = $030B;
  Timer_0:                       Integer = $030C;
  Timer_1:                       Integer = $030D;
  Timer_Control:                 Integer = $030F;

var
  Check:                         Byte;
  DMA_1:                         Integer;
  DMA_2:                         Integer;
  DMA_3:                         Integer;
  SegPart:                       Integer;
  OfsPart:                       Integer;
  Page:                          Byte;
  Address_Lo:                    Byte;
  Address_Hi:                    Byte;
  Address:                       Integer absolute Address_Lo;

begin

{ First disable NMI on PC for parity checking }

  Port [ $A0 ] := 0;

{ "Turn off" timer for duration of reset to prevent spurious NMI

  Port [ Timer_Control ] := 54;
  Port [ Timer_Control ] := 118;
  Port [ Timer_0 ] := 255;
  Port [ Timer_0 ] := 255;
  Port [ Timer_1 ] := 255;
  Port [ Timer_1 ] := 255;                                  }

{ reset 6801 data acquisition board }

  Port [ DMA_Control_Register ] := 66;
  Delay(1);
  Port [ Port_B ] := 8;
  Delay(1);
  Port [ Port_B ] := 0;
```

```
{ disable DREQ to prevent spurious transfers }

{ Port [ Mask_Register ] := 5; }
  Port [ Mask_Register ] := 7;

{ set dma mode }

  Port [ Mode_Register ] := 85;
  Port [ Mode_Register ] := 87;

{ write starting address for levels 1 and 3, lo byte first }

  SegPart := Seg ( DMA_1 );
  OfsPart := Ofs ( DMA_1 );
{ Writeln ( SegPart, '     ', OfsPart ); }

  Page := SegPart shr 12;
  Address := SegPart shl 4 + OfsPart;
{ Writeln('     ',Page,'     ',Address); }

{ Port [ Address_Register_1 ] := 0;
  Port [ Address_Register_1 ] := 0; }
  Port [ Address_Register_3 ] := Address_Lo;
  Port [ Address_Register_3 ] := Address_Hi;

{ write byte count for levels 1 and 3, lo byte first }

{ Port [ Byte_Count_Register_1 ] := 10;
  Port [ Byte_Count_Register_1 ] := 0;  }
  Port [ Byte_Count_Register_3 ] := 6;
  Port [ Byte_Count_Register_3 ] := 0;

{ set page registers }

{ Port [ Page_Register_1 ] := hi 4 bits of address }
  Port [ Page_Register_3 ] := Page;

{ now set mode for PDMA-16 board }

  Port [ DMA_Control_Register ] := 192;

{ set any interrupts here.  If set, install immediately after. }

  Interrupt_Control := 0;

{ set up timer for periodic measurements, 100 Hz sample rate }

  Port [ Timer_Control ] := 54;
  Port [ Timer_Control ] := 118;
  Port [ Timer_0 ] := 16;
  Port [ Timer_0 ] := 39;
  Port [ Timer_1 ] := 10;
  Port [ Timer_1 ] := 0;
```

```
{ clear masks to enable DREQ so DMA transfers can be made }

{ Port [ Mask_Register ] := 1; }
  Port [ Mask_Register ] := 3;

{ now start reading the DMA }

  repeat
    repeat
      Check := Port [ Port_B ];
      Check := Check and 4;
      until Check = 4;
    Delay(500);
    Writeln ( DMA_1, '     ', DMA_2, '     ',  DMA_3 );
    until KeyPressed;

  end.
```

```
program Jog;

const
  IRQ:                    Byte = $FB;
  Reset:                  Byte = $F7;
  Read_AD:                Byte = $0E;
  Read_AD_DMA:            Byte = $1E;
  Com_Wait:               Byte = $04;
  Write_Wait:             Byte = $02;
  Read_Wait:              Byte = $05;
  PDMA_Control:           Integer = $0309;
  Base_Vert_Lo:           Integer = $0310;
  Base_Vert_Hi:           Integer = $0311;
  Elbow_Lo:               Integer = $0312;
  Elbow_Hi:               Integer = $0313;
  DT2801_Data_Reg:        Integer = $02EC;
  DT2801_Com_Reg:         Integer = $02ED;

var
  Move:                   Integer;
  Base_Angle:             Real;
  Elbow_Angle:            Real;
  Base_Torque:            Real;
  Elbow_Torque:           Real;
  Choice:                 Char;

{ abbreviated name      hex address,    integer address
                                        of port for i/o }


procedure Setup_Controller;

{$I Graph.P}

const
  Enable:                 Byte = $FE;
  Ready:                  Byte = $04;
  Data_In_Full:           Byte = $02;
  Data_Out_Ready:         Byte = $01;
  Write_DA_Imm:           Byte = $08;
  Set_AD:                 Byte = $0D;
  Set_DA:                 Byte = $09;
  Com_Stop:               Byte = $0F;
  Com_Reset:              Byte = $00;
  Set_Clock:              Byte = $03;
  Stop_Mav_Lo:            Byte = $00;
  Stop_Mav_Hi:            Byte = $80;
  Stop_PMI_Lo:            Byte = $00;
  Stop_PMI_Hi:            Byte = $08;

var
  Junk:                   Byte;
  Enable_Check:           Char;
```

```
begin
  ClrScr;

  Port [ DT2801_Com_Reg ] := Com_Stop;
  Junk := Port [ DT2801_Data_Reg ];
  write('1');
  Port [ DT2801_Com_Reg ] := Set_AD;
  write('2');
  repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
  Port [ DT2801_Data_Reg ] := 0;
  write('3');
  repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
  Port [ DT2801_Data_Reg ] := 1;
  write('4');
  repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
  Port [ DT2801_Data_Reg ] := 5;
  write('5');
  repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
  Port [ DT2801_Data_Reg ] := 5;
  write('6');
  repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
  Port [ DT2801_Data_Reg ] := 0;
  write('7');
  Delay(100);


{ now set all D/A s to zero volts output for enable... }

  Port [ DT2801_Com_Reg ] := Write_DA_Imm;
  write('8');
  repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
  Port [ DT2801_Data_Reg ] := 0;
  write('9');
  repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
  Port [ DT2801_Data_Reg ] := Stop_PMI_Lo;
  repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
  Port [ DT2801_Data_Reg ] := Stop_PMI_Hi;
  Port [ Base_Vert_Lo ] := Stop_Mav_Lo;
  Port [ Base_Vert_Hi ] := Stop_Mav_Hi;
  Port [ Elbow_Lo ] := Stop_Mav_Lo;
  Port [ Elbow_Hi ] := Stop_Mav_Hi;

  GotoXY(19,11);
  Write('Press and hold black button on controller');
  GotoXY(19,13);
  Write('and then press <ESC> to enable controller.');
  repeat
    read(Kbd, Enable_Check);
    until Enable_Check = chr(27);
  Port [ PDMA_Control ] := Enable;
  Delay(500);
  Port [ PDMA_Control ] := 0;
  ClrScr;
```

```
{  Setting up D/A, A/D converter.  }

  GotoXY(10,10);
  Write('Controller now enabled.  Press any key to continue...');
  repeat until KeyPressed;

{  DT2801-A board now set up for 5 A/D conversions per read, no DMA  }

  end;


procedure Disable_Controller;

const
  Disable:                  Byte = $FD;

{$I Graph.P}

begin
  ClrScr;
  GotoXY(28,10);
  Write('Disabling Controller.');
  Port [ PDMA_Control ] := Disable;
  Delay(500);
  Port [ PDMA_Control ] := 0;
  GotoXY(10,12);
  Write('Controller now disabled.  Press any key to continue...');
  repeat
    until KeyPressed;
  end;

procedure Jog;

const
  Ready:                    Byte = $04;
  Data_In_Full:             Byte = $02;
  Data_Out_Ready:           Byte = $01;
  Set_AD:                   Byte = $0D;
  Set_DA:                   Byte = $09;
  Com_Stop:                 Byte = $0F;
  Com_Reset:                Byte = $00;
  Set_Clock:                Byte = $03;
  Write_DA_Imm:             Byte = $08;
  Com_Wait:                 Byte = $04;
  Read_Wait:                Byte = $05;
  Stop_Hi_PMI:              Byte = $08;
  Stop_Lo_PMI:              Byte = $00;
  Stop_Hi_Mav:              Byte = $80;
  Stop_Lo_Mav:              Byte = $00;
  Base_Vert_Lo:             Integer = $0310;
  Base_Vert_Hi:             Integer = $0311;
  Base_Hor:                 Integer = $02EC;
  Elbow_Lo:                 Integer = $0312;
  Elbow_Hi:                 Integer = $0313;
  DTA_2801:                 Integer = $02EC;
```

```
  PDMA_Control:           Integer = $0309;

var
  Speed:                  Integer;
  Speed_Pos_Hi_PMI:       Byte;
  Speed_Pos_Lo_PMI:       Byte;
  Speed_Neg_Hi_PMI:       Byte;
  Speed_Neg_Lo_PMI:       Byte;
  Speed_Pos_Hi_Mav:       Byte;
  Speed_Pos_Lo_Mav:       Byte;
  Speed_Neg_Hi_Mav:       Byte;
  Speed_Neg_Lo_Mav:       Byte;
  Motor:                  char;

{$I Graph.P}

begin
  ClrScr;
  GotoXY(10,12);
  Write('What is the desired motor speed? (0-2047 please) ');

  repeat
    readln(Speed);
    until (Speed >= 0) and (Speed <= 2047);

  Speed_Pos_Hi_Mav  := (2048 + Speed) shr 4;
  Speed_Pos_Lo_Mav  := ( (2048 + Speed) - Speed_Pos_Hi_Mav shl 4) shl 4;
  Speed_Neg_Hi_Mav  := (2048 - Speed) shr 4;
  Speed_Neg_Lo_Mav  := ( (2048 - Speed) - Speed_Pos_Hi_Mav shl 4) shl 4;
  Speed_Pos_Hi_PMI  := (2048 + Speed) shr 8;
  Speed_Pos_Lo_PMI  := (2048 + Speed) - Speed_Pos_Hi_PMI shl 8;
  Speed_Neg_Hi_PMI  := (2048 - Speed) shr 8;
  Speed_Neg_Lo_PMI  := (2048 - Speed) - Speed_Neg_Hi_PMI shl 8;

  ClrScr;
  GotoXY(31,1);
  Writeln(' _______________ ');
  GotoXY(31,2);
  Writeln('|               |');
  GotoXY(31,3);
  Writeln('|     Speed     |');
  GotoXY(31,4);
  Writeln('|_______________|');
  GotoXY(31,5);
  Writeln('|               |');
  GotoXY(31,6);
  Writeln('|               |');
  GotoXY(31,7);
  Writeln('|_______________|');
  GotoXY(37,6);
  Write(Speed);
  GotoXY(10,9);
  Writeln(' _______________      _______________      _______________ ');
  GotoXY(10,10);
  Writeln('|               |    |               |    |               |');
```

```
GotoXY(10,11);
Writeln('|   Base Ver    |     |  Base Hor      |    |     Elbow      |');
GotoXY(10,12);
Writeln('|_______________|     |________________|    |________________|');
GotoXY(10,13);
Writeln('|               |     |                |    |                |');
GotoXY(10,14);
Writeln('|    8 --- +    |     |   6 --- +      |    |    7 --- +     |');
GotoXY(10,15);
Writeln('|    2 --- -    |     |   4 --- -      |    |    3 --- -     |');
GotoXY(10,16);
Writeln('|_______________|     |________________|    |________________|');
GotoXY(10,17);
Writeln('|               |     |                |    |                |');
GotoXY(10,18);
Writeln('|               |     |                |    |                |');
GotoXY(10,19);
Writeln('|_______________|     |________________|    |________________|');
GotoXY(16,23);
Write('         Press <ESC> to exit to main menu');

repeat

  read(Kbd,Motor);

  case Motor of

    '8': begin
           Port [ Base_Vert_Lo ] := Speed_Pos_Lo_Mav;
           Port [ Base_Vert_Hi ] := Speed_Pos_Hi_Mav;
           Port [ Elbow_Lo ] := Stop_Lo_Mav;
           Port [ Elbow_Hi ] := Stop_Hi_Mav;
           Port [ DT2801_Com_Reg ] := Write_DA_Imm;
           repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
           Port [ DT2801_Data_Reg ] := 0;
           repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
           Port [ DT2801_Data_Reg ] := Stop_Lo_PMI;
           repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
           Port [ DT2801_Data_Reg ] := Stop_Hi_PMI;
           GotoXY(10,18);
           Write('|       +       |     |     Stop       |    |      Stop
|');
         end;

    '2': begin
           Port [ Base_Vert_Lo ] := Speed_Neg_Lo_Mav;
           Port [ Base_Vert_Hi ] := Speed_Neg_Hi_Mav;
           Port [ Elbow_Lo ] := Stop_Lo_Mav;
           Port [ Elbow_Hi ] := Stop_Hi_Mav;
           Port [ DT2801_Com_Reg ] := Write_DA_Imm;
           repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
           Port [ DT2801_Data_Reg ] := 0;
           repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
           Port [ DT2801_Data_Reg ] := Stop_Lo_PMI;
           repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
           Port [ DT2801_Data_Reg ] := Stop_Hi_PMI;
```

```
        GotoXY(10,18);
        Write('|        -      |    |       Stop      |    |       Stop
|');
      end;

  '4': begin
        Port [ Base_Vert_Lo ] := Stop_Lo_Mav;
        Port [ Base_Vert_Hi ] := Stop_Hi_Mav;
        Port [ Elbow_Lo ] := Stop_Lo_Mav;
        Port [ Elbow_Hi ] := Stop_Hi_Mav;
        Port [ DT2801_Com_Reg ] := Write_DA_Imm;
        repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
        Port [ DT2801_Data_Reg ] := 0;
        repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
        Port [ DT2801_Data_Reg ] := Speed_Pos_Lo_PMI;
        repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
        Port [ DT2801_Data_Reg ] := Speed_Pos_Hi_PMI;
        GotoXY(10,18);
        Write('|     Stop      |    |        +        |    |       Stop
|');
      end;

  '6': begin
        Port [ Base_Vert_Lo ] := Stop_Lo_Mav;
        Port [ Base_Vert_Hi ] := Stop_Hi_Mav;
        Port [ Elbow_Lo ] := Stop_Lo_Mav;
        Port [ Elbow_Hi ] := Stop_Hi_Mav;
        Port [ DT2801_Com_Reg ] := Write_DA_Imm;
        repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
        Port [ DT2801_Data_Reg ] := 0;
        repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
        Port [ DT2801_Data_Reg ] := Speed_Neg_Lo_PMI;
        repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
        Port [ DT2801_Data_Reg ] := Speed_Neg_Hi_PMI;
        GotoXY(10,18);
        Write('|     Stop      |    |        -        |    |       Stop
|');
      end;

  '7': begin
        Port [ Base_Vert_Lo ] := Stop_Lo_Mav;
        Port [ Base_Vert_Hi ] := Stop_Hi_Mav;
        Port [ Elbow_Lo ] := Speed_Pos_Lo_Mav;
        Port [ Elbow_Hi ] := Speed_Pos_Hi_Mav;
        Port [ DT2801_Com_Reg ] := Write_DA_Imm;
        repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
        Port [ DT2801_Data_Reg ] := 0;
        repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
        Port [ DT2801_Data_Reg ] := Stop_Lo_PMI;
        repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
        Port [ DT2801_Data_Reg ] := Stop_Hi_PMI;
        GotoXY(10,18);
        Write('|     Stop      |    |      Stop       |    |        +
|');
      end;
```

```
            Port [ Elbow_Lo ] := Speed_Neg_Lo_Mav;
            Port [ Elbow_Hi ] := Speed_Neg_Hi_Mav;
            Port [ DT2801_Com_Reg ] := Write_DA_Imm;
            repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
            Port [ DT2801_Data_Reg ] := 0;
            repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
            Port [ DT2801_Data_Reg ] := Stop_Lo_PMI;
            repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
            Port [ DT2801_Data_Reg ] := Stop_Hi_PMI;
            GotoXY(10,18);
            Write('|     Stop     |    |     Stop     |   |          -
|');
          end;

      else

        begin
          Port [ Base_Vert_Lo ] := Stop_Lo_Mav;
          Port [ Base_Vert_Hi ] := Stop_Hi_Mav;
          Port [ Elbow_Lo ] := Stop_Lo_Mav;
          Port [ Elbow_Hi ] := Stop_Hi_Mav;
          Port [ DT2801_Com_Reg ] := Write_DA_Imm;
          repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
          Port [ DT2801_Data_Reg ] := 0;
          repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
          Port [ DT2801_Data_Reg ] := Stop_Lo_PMI;
          repeat until Port [ DT2801_Com_Reg ] <> Data_In_Full;
          Port [ DT2801_Data_Reg ] := Stop_Hi_PMI;
          GotoXY(10,18);
          Write('|     Stop     |    |     Stop     |   |      Stop      |
');
        end;

      end;

      until Motor = chr(27);
    end;

  {$I Graph.P}

  begin

    repeat

      ClrScr;
      GotoXY(28,3);
      Write('---------------------');
      GotoXY(34,4);
      Write('Main Menu');
      GotoXY(28,5);
      Write('---------------------');
      GotoXY(36,8);
      Write('Setup');
      GotoXY(35,10);
      Write('Disable');
      GotoXY(37,12);
      Write('Jog');
```

```
    GotoXY(37,14);
    Write('Quit');
    GotoXY(14,23);
    Write('Make selection by pressing first letter of option');

    repeat
      Choice := ' ';
      read(Kbd,Choice);
      until UpCase(Choice) in ['S','D','J','Q'];
    Choice := UpCase(Choice);

    case Choice of

      'S': Setup_Controller;

      'D': Disable_Controller;

      'J': Jog;

      'Q': Disable_Controller;

    end;

    until Choice = 'Q';

end.
```

6801. ASM

```
;       D.M.A. REQUEST LINE.  EACH TIME A DATA TRANSFER
;       IS NEEDED, PORT 2 BIT 4 IS SET TO LOGIC 1.
;       PORT 2 BIT 4 MUST BE SET BACK TO LOGIC 4 AFTER
;       EACH BYTE TRANSFER TO RESET THE D.M.A. REQUEST
;       LINE.
;
;************************************************************
;
;************************ ELBOW ***************************
NMI     LDAA    #00H    ;2 prepare data-not-ready
        STAA    PORT2   ;3 send data-not-ready
        LDD     D000H   ;5 start with elbow joint
ELBOW   LSRD            ;3 shift right
        LSRD            ;3 shift right
        STAA    TEMP    ;3 store unaltered high byte
        ANDA    #03H    ;2
        BNE     PASS1   ;3 branch if not zero
        LDAA    DEC1    ;3 load decoder 1 previous value
        ANDA    #03H    ;2 mask out all but 2 highest bits
        BNE     OUT1    ;3 branch if not equal, no overflow
        LDAA    OVDEC1  ;3 load overflow count, dec1
        ADDA    #04H    ;2 add 04H to acc. a for 1 more ovfl
        STAA    OVDEC1  ;3 save new overflow count
        BRA     OUT1    ;3
PASS1   LDAA    DEC1    ;3 load decoder 1 previous value
        ANDA    #03H    ;2 mask out all but 2 high bits
        BNE     OUT1    ;3 branch if not zero
        LDAA    OVDEC1  ;3 load overflow count, dec1
        SUBA    #04H    ;2 sub 04H from acc. a, 1 less ovfl
        STAA    OVDEC1  ;3 save new overflow count
OUT1    LDAA    OVDEC1  ;3 load overflow count
        ADDA    TEMP    ;6 add hi byte to overflow count
        STAA    PORT1   ;3 store hi byte in output port
        LDAA    #08H    ;2 load 4th bit set
        STAA    PORT2   ;3 send d.m.a. request
        LDAA    #00H    ;2 reset port 2 bit 4
        STAA    PORT2   ;3 d.m.a. request now reset
        LDAA    #08H    ;2 load 4th bit set
        STAB    PORT1   ;3 store lo byte in output port
        STAA    PORT2   ;3 send d.m.a. request
        LDAA    #00H    ;2 reset port 2 bit 4
        STAA    PORT2   ;3 d.m.a. request now reset
;****************** BASE VERTICAL ***********************
BASVER  LDD     B000H   ;5 now do vertical
        LSRD            ;3 shift right
        LSRD            ;3 shift right
        STAA    TEMP    ;3 store unaltered high byte
        ANDA    #03H    ;2
        BNE     PASS2   ;3 branch if not zero
        LDAA    DEC2    ;3 load decoder 2 previous value
        ANDA    #03H    ;2 mask out all but 2 high bits
        BNE     OUT2    ;3 branch if not equal, no overflow
        LDAA    OVDEC2  ;3 load overflow count, dec2
        ADDA    #04H    ;2 add 04H to acc. a for 1 more ovfl
        STAA    OVDEC2  ;3 save new overflow count
```

```
;THIS PROGRAM CONTAINS 6801 SETUP ROUTINES AS WELL
;AS TEST AND MEMORY EXAMINE ROUTINES FOR EVALUATION
;OF SYSTEM PERFORMANCE AND VERIFICATION OF PROPER
;FUNCTION OF THE 6801 SLAVE ENCODER/DECODER BOARD.
;
;**********************************************************
;********************** MAIN PROGRAM **********************
;**********************************************************
;
SERIO   .EQU    F7EAH  ;serial i/o configure
SRMR    .EQU    10H    ;serial rate and mode control
SERRX   .EQU    12H    ;serial receive register
SERTX   .EQU    13H    ;serial transmit register
OUTPUT  .EQU    FFFFH  ;all outputs
DDR1    .EQU    00H    ;port 1 data direction register
PORT1   .EQU    02H    ;port 1 data register
DDR2    .EQU    01H    ;port 2 data direction register
PORT2   .EQU    03H    ;port 2 data register
DDR4    .EQU    05H    ;port 4 data direction register
TRCS    .EQU    11H    ;trans, rec control and status
STACK   .EQU    00FFH  ;location of stack
;******************** MEMORY SETUP ************************
        .ORG    0080H
TEMP    .BLKB   1
DEC1    .BLKB   1
OVDEC1  .BLKB   1
DEC2    .BLKB   1
OVDEC2  .BLKB   1
DEC3    .BLKB   1
OVDEC3  .BLKB   1
MEMSTT  .BLKW   1
MEMSTP  .BLKW   1
;----------------------------------------------------------
        .ORG    F800H
START   LDS     #STACK ;set stack pointer for interrupt
        LDAA    #00H
        STAA    TRCS   ;serial port now disabled
        LDD     #OUTPUT
        STD     DDR1   ;port 1 now output
        LDAA    #FFH
        STAA    DDR4   ;port 4 now output
WAIT    WAI            ;wait for interrupt
        BRA     WAIT   ;always go back to wait for int.
;**********************************************************
;***************** NMI SERVICE ROUTINE ********************
;**********************************************************
;
;       THIS ROUTINE SERVICES THE INTERRUPT CREATED BY
;       THE IBM-PC CONTROL PROGRAM AND COLLECTS THE
;       ENCODED POSITION OF EACH DEGREE OF FREEDOM.
;       THE EONCODED POSITIONS ARE DECODED AND CHECKED
;       FOR OVERFLOW OR UNDERFLOW AND ADJUSTED
;       APPROPRIATELY.  THE DATA IS THEN FED BACK
;       TO THE IBM-PC AS TWO 8 BIT BYTES, UNDER IBM-PC
;       D.M.A. CONTROL.  PORT 2 BIT 4 CONTROLS THE
```

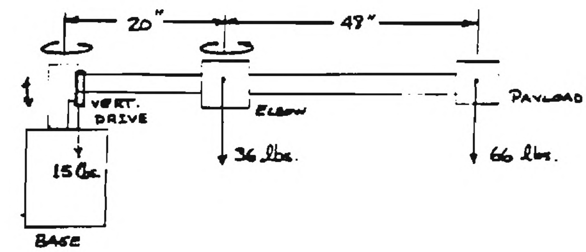
```
        BRA     OUT2    ;3
PASS2   LDAA    DEC2    ;3 load decoder 2 previous value
        ANDA    #03H    ;2 mask out all but 2 high bits
        BNE     OUT2    ;3 branch if not zero
        LDAA    OVDEC2  ;3 load overflow count, dec2
        SUBA    #04H    ;2 sub 04H from acc. a, 1 less ovfl
        STAA    OVDEC2  ;3 save new overflow count
OUT2    LDAA    OVDEC2  ;3 load overflow count
        ADDA    TEMP    ;6 add hi byte to overflow count
        STAA    PORT1   ;3 store hi byte in output port
        LDAA    #08H    ;2 load 4th bit set
        STAA    PORT2   ;3 send d.m.a. request
        LDAA    #00H    ;2 reset port 2 bit 4
        STAA    PORT2   ;3 d.m.a. request now reset
        LDAA    #08H    ;2 load 4th bit set
        STAB    PORT1   ;3 store lo byte in output port
        STAA    PORT2   ;3 send d.m.a. request
        LDAA    #00H    ;2 reset port 2 bit 4
        STAA    PORT2   ;3 d.m.a. request now reset
;****************** BASE HORIZONTAL ********************
BASHOR  LDD     9000H   ;5 finish with base horiz.
        LSRD            ;3 shift right
        LSRD            ;3 shift right
        STAA    TEMP    ;3 store unaltered high byte
        ANDA    #03H    ;2
        BNE     PASS3   ;3 branch if not zero
        LDAA    DEC3    ;3 load decoder 3 previous value
        ANDA    #03H    ;2 mask out all but 2 high bits
        BNE     OUT3    ;3 branch if not equal, no overflow
        LDAA    OVDEC3  ;3 load overflow count, dec3
        ADDA    #04H    ;2 add 04H to acc. a for 1 more ovfl
        STAA    OVDEC3  ;3 save new overflow count
        BRA     OUT3    ;3
PASS3   LDAA    DEC3    ;3 load decoder 3 previous value
        ANDA    #03H    ;2 mask out all but 2 high bits
        BNE     OUT3    ;3 branch if not zero
        LDAA    OVDEC3  ;3 load overflow count, dec3
        SUBA    #04H    ;2 sub 04H from acc. a, 1 less ovfl
        STAA    OVDEC3  ;3 save new overflow count
OUT3    LDAA    OVDEC3  ;3 load overflow count
        ADDA    TEMP    ;6 add hi byte to overflow count
        STAA    PORT1   ;3 store hi byte in output port
        LDAA    #08H    ;2 load 4th bit set
        STAA    PORT2   ;3 send d.m.a. request
        LDAA    #00H    ;2 reset port 2 bit 4
        STAA    PORT2   ;3 d.m.a. request now reset
        LDAA    #08H    ;2 load 4th bit set
        STAB    PORT1   ;3 store lo byte in output port
        STAA    PORT2   ;3 send d.m.a. request
        LDAA    #00H    ;2 reset port 2 bit 4
        STAA    PORT2   ;3 d.m.a. request now reset
;================= now all data has been sent ============
        LDAA    #10H    ;2 prepare data sent signal
        STAA    PORT2   ;3 send data-sent to IBM-PC
DUMMY   RTI             ;10 return from interrupt
```

```
;*********************************************************
;
;       ONE READ CYCLE OF ENCODERS NOW FINISHED
;
;*********************************************************
;****************** MEMORY EXAMINE ***********************
;*********************************************************
;
;       THIS ROUTINE SERVICES AN IRQ TYPE INTERRUPT
;       FOR MEMORY EXAMINATION PURPOSES.  IT WILL TAKE
;       A FOUR CHARACTER ASCII STRING AND CONVERT IT
;       TO HEXADECIMAL FOR A STARTING MEMORY LOCATION
;       TO EXAMINE.  IT THEN TAKES ANOTHER FOUR CHARACTERS
;       FOR THE ENDING MEMORY LOCATION AND THEN FETCHES
;       THOSE MEMORY LOCATIONS, DISPLAYING THEM ON A
;       VIC-20 OR COMMODORE-64 SCREEN.  ALL COMMUNICATION
;       IS DONE AT 300 BAUD.
;
;*********************************************************
IRQ     LDD     #SERIO ;load data form, sp, conf. tx, rx
        STD     SRMR   ;serial mode, tx, rx enabled
        LDAA    TRCS
INPUT   ROLA
        BCC     INPUT
        LDAA    SERRX
        ASLA
        BMI     ALPHA  ;branch if neg set indicating alpha
        LSRA
        CMPA    #0DH
        BEQ     FETCH
        CMPA    #20H
        BEQ     LODINX
        CMPA    #30H
        BLT     INPUT
        CMPA    #39H
        BGT     INPUT
        SUBA    #30H
        BRA     RTN
ALPHA   LSRA
        CMPA    #41H
        BLT     INPUT
        CMPA    #46H
        BGT     INPUT
        SUBA    #37H
RTN     RTI
;*********************************************************
;*********************** OUTCHAR *************************
;*********************************************************
;
;       * - OUTPUT ONE BYTE AS TWO HEX ASCII CHARS
;
;---------------------------------------------------------
OUTCH1  TAB
        LSRA
        LSRA
```

```
        LSRA
        LSRA
        BSR     OUTP
OUTCH2  TBA
        ANDA    #$FH
        BSR     OUTP
        LDAA    #$20H
        BSR     OUTCH
        RTS
;************************************************************
;*********************** OUTPUT ***************************
;************************************************************
;
;       * - CONVERT TO ASCII FROM HEX AND OUTPUT
;
;------------------------------------------------------------
OUTP    CMPA    #$A
        BGE     ALPHA1
        ADDA    #$30H
        BRA     OUTCH
ALPHA1  ADDA    #$37H
OUTCH   LDAB    TRCS
        ROLB
        ROLB
        ROLB
        BCC     OUTCH
        STAA    SERTX
        RTS
;************************************************************
;*********************** LOAD INDEX ***********************
;************************************************************
LODINX  LDX     #MEMSTT ;load starting addr. for mem exch
        BRA     RTN
;************************************************************
;*********************** MEMORY FETCH *********************
;************************************************************
FETCH   LDAA    0,X
        BSR     OUTCH1
        INX
        CPX     #MEMSTP
        BNE     FETCH
        BRA     RTN
;************************************************************
;*********************** VECTOR TABLE *********************
;************************************************************
        .ORG    $FFF0H
VECTR   FDB     DUMMY
        FDB     DUMMY
        FDB     DUMMY
        FDB     DUMMY
        FDB     IRQ
        FDB     DUMMY
        FDB     NMI
        FDB     START
        .END
```

Appendix G

SIZING CALCULATIONS FOR LINKS AND DRIVE SYSTEMS



PERFORMANCE OBJECTIVE: Each joint should be capable of accelerating a 30 kg payload at 32 ft/sec². The necessary motor torque requirements will be determined in this section.

BASE DRIVE: The fully extended arm position is used to determine the joint torques, since this position requires the greatest torque to achieve a given acceleration of the payload. For the base, all inertias due to masses other than the payload and elbow are neglected.

$\tau = I\alpha \qquad I\,(\text{in-lb}\cdot\text{sec}^2) = \left(\frac{36}{386}\right)(20)^2 + \left(\frac{66}{386}\right)(68)^2$

$\alpha = \frac{386}{68}\ \text{sec}^{-2} \qquad \Rightarrow \tau = 4,720\ \text{in-lb}$

With a 200 : 1 Harmonic Drive (rated at 75% efficiency), the necessary base motor torque is

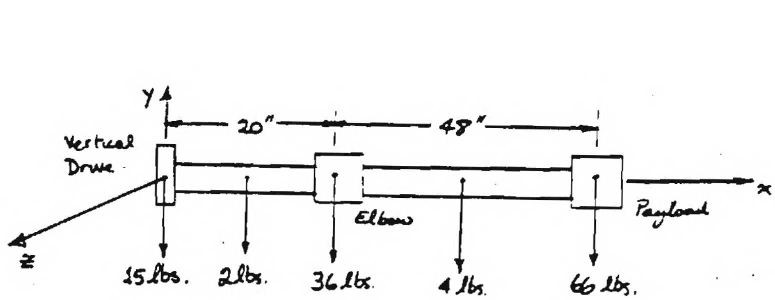
$\frac{4,720}{(0.75)(200)} = 31.5\ \text{in-lb}.$

ELBOW JOINT: If the upper arm is fixed the elbow only has to accelerate the payload.

$\tau = I\alpha \quad ; \quad I = \left(\frac{66}{386}\right)(48)^2\ \text{in}\cdot\text{lb}\cdot\text{s}^2 \quad ; \quad \alpha = \frac{386}{48}\ \text{s}^{-2}$

$\tau = 3,168$ in-lb. ; With a 75% efficient 200 : 1 Harmonic Drive, the required elbow motor torque is

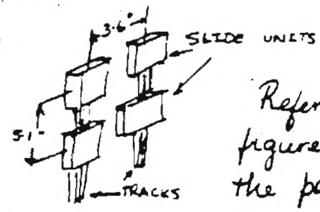
$\frac{3,168}{(0.75)(200)} = 21.1\ \text{in-lb}.$



VERTICAL DRIVE: The total weight to be moved by the vertical drive is (in lb_f) (15 + 2 + 36 + 4 + 66) = 123 lbs. For 1g upward acceleration, the force on the vertical drive assembly is (2)(123) = 246 lbs.

The torque required to produce a force F with a ball screw is given by $\tau = \frac{F d_m}{2}\left(\frac{l + \mu \pi d_m}{\pi d_m - \mu l}\right)$, where d_m is the mean diameter of the screw, l is the screw lead, μ is the coefficient of friction. For a Saginaw 0375-125-B2 ball screw with $l = 0.125"$, $d_m = 0.337"$, and $\mu = 0.007$, the torque needed to raise 246 lbs is 5.2 in-lb. If the motor is driving the ball screw through a 90% efficient timing belt with 2:1 speed reduction, the required motor torque is $\frac{5.2}{2(0.9)} = 2.9$ in-lb

Linear Motion Units:



Referring to the figure at the top of the page, it can be seen that the slide units must resist forces due to moments about the y and z axes.

$M_y = \tau_{base} = 4{,}720$ in-lb.

$M_z = (2)\left[(36)(20) + (2)(10) + (4)(44) + (66)(68)\right]$

$= 8{,}172$ in-lb

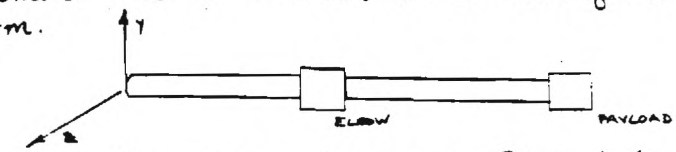
If M_y and M_z are applied simultaneously, the force applied on two of the four slide units is $F = \frac{M_z}{5.1"} + \frac{M_y}{3.6"} = 2{,}913$ lbs.

The following table shows the capacities of the drive system components relative to the torque and force requirements calculated earlier.

COMPONENT	MODEL	REQUIRE-MENTS	RATED CAPACITY	PEAK CAPACITY	SAFETY FACTOR	UNITS
Base motor	PMI U12 M4H	31.5	15.5	175	5.	in-lb.
Base harmonic drive	HDC 4M-200-2	4,720	3,300	8,530	1.	in-lb
Vertical motor	MAVILOR MT50	2.9	4.3	28.0	9	in-lb
Elbow motor	MAVILOR MT80	21.1	4.3	28.0	1.3	in-lb.
Elbow harmonic drive	HDC 4M-200-2	3,168	3,300	8,530	2.	in-lb.
Ball screw	SAGINAW 0375-125-02	246	272	2,830	11.	lb_f
Slide units	LINEAR RAIL WAY LRW 20	2,913	3,940	4,850	1.	lb_f

It can be seen that all the drive components have enough capacity to meet the performance objectives of the arm.

TUBULAR LINKS: The link sections are most highly stressed at the vertical drive flange. Here, the link may have to withstand the maximum base moment and the maximum moment due to vertical acceleration of the arm.



$M_y = 4720$ in-lb ; $M_z = 8,172$ in-lb

$M_{TOTAL} = \sqrt{M_y^2 + M_z^2} = 9,437$ in-lb

$M_{cr} = \pi \sigma_{max} r^2 t_o$, where σ_{max} is the tensile strength of the beam material, r is the average diameter of the beam material, and t_o is the wall thickness of the beam.

For Al 6061-T6, $\sigma_{max} = 40$ kpsi

$r = 3.417''$, $t_o = 0.083'' \Rightarrow M_{cr} = 32,800$ in-lb.

Since the maximum design moment is 9,400 in-lb this results in a safety factor of 3.5.